Ash, Gas and Computers: the vulnerability of laptop computers to volcanic hazards

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Frontispiece

Volcanic eruption plume from Eyjafjallajökull, Iceland in 2010 (Lucas Jackson, Reuters)

Abstract

Volcanic eruptions are powerful, uncontrollable natural events which produce a number of hazards that can impact upon all aspects of society, including critical infrastructure. The most widespread and disruptive of these hazards is volcanic ashfall. Direct ashfall impacts, even minor, can cause multiple knock-on effects throughout all critical infrastructure sectors leading to disruption of these services, on which society relies. However with appropriate volcanic risk management strategies, these impacts can be lessened.

Electronic equipment, including laptop computers, are a common and vital component in all critical infrastructure sectors, field based volcanic research and wider society. Therefore, it is important to understand how laptops will function in volcanic environments. This thesis assesses the vulnerability of laptop computers to volcanic ash and gas hazards through field and laboratory based experimentation and the development of quantitative risk assessments metrics.

Laboratory based ash vulnerability experiments were carried out in the Volcanic Ash Testing Facility, University of Canterbury, using a mass produced basalt 'pseudo ash', which is physically and chemically analogous to fresh volcanic ash. Each laptop was exposed to ash for 100-160 hours at fall rates of ~500 g/m^2 h. None of the ten laptops used sustained any permanent damage from volcanic ash, however, three shutdown temporarily due to overheating. This was because laptops only contain a few small ventilation holes which prevent large quantities of ash from entering the laptops. However, ash contamination reduced functionality of keyboards, CD drives and some cooling fans as these are open to the environment or located close to ventilation holes. Wet ash, known to cause short circuits of electrical equipment, was not able to enter the laptops because it is less mobile than dry ash. Functionality was retained with the use of simple mitigation techniques such as placing laptops inside heavy duty polyethylene bags.

Volcanic gas vulnerability experiments were undertaken at White Island, New Zealand. Three laptops were exposed to high concentrations of volcanic gases for ~5 hours. None however, sustained any permanent damage, due to the limited quantity of gas that could enter the laptop, although metal components on the outside of the laptop sustained minor corrosion.

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Chapter One – Introduction

1.1. Context of Study

Volcanic eruptions are powerful, uncontrollable natural events which produce a number of hazards that can impact upon all aspects of society, including critical infrastructure. Volcanic hazards such as pyroclastic density currents, gas emissions, lahars and ballistics are the most destructive and dangerous, and have accounted for the majority of the recorded deaths associated with volcanic eruptions (Hansell *et al.*, 2006). Volcanic ash, however, rarely causes loss of life and is considered a disruptive hazard rather than a destructive one. Due to their widespread nature, volcanic ashfalls can cause disruption to critical infrastructure (e.g. water and waste water systems, electrical distribution networks, transportation, communication networks, etc.), buildings and primary production across large geographic areas, leading to significant societal impacts (Wilson *et al.*, 2011, *in press*). However, experience from around the world has demonstrated that these impacts can be reduced with appropriate risk reduction techniques.

Volcanic risk reduction has successfully reduced volcanic hazard related deaths through increased volcanic surveillance, public education and effective and timely warnings and evacuations (ESCAP, 1999). In some cases, damage from volcanic hazards has been lowered through hazard mapping and analysis, land use planning and implementation of engineering works. One of the areas that has not been studied in great detail, is the disruptive impacts of volcanic ashfall on society, particularly critical infrastructure, on which society relies. It is known from experience that when certain critical infrastructure sectors are disrupted by volcanic ash, the impacts can be widespread and may cause flow-on effects to other sectors. For example, the recent eruption of Eyjafjallajökull, Iceland in 2010, dispersed volcanic ash into European airspace forcing it to be closed, causing major disruptions to industries that rely on air travel.

Much of the understanding of volcanic ash impacts is from field observations and anecdotal accounts, which are qualitative in nature. Very little quantitative research has been undertaken to determine exactly how critical infrastructure will perform in a range of conditions in future ashfall events. There is even less knowledge surrounding how volcanic gases affect critical infrastructure.

One area that has not been studied quantitatively is volcanic ash and gas hazard impacts on electronic equipment. Electronic equipment is used extensively in nearly all areas of society and within critical infrastructure sectors, primarily for system control but also for administration. As technology develops through micronisation and increased performance, electronics will be increasingly relied upon and deployed in areas exposed to volcanic ash and gas hazards. Thus, it is vitally important that their performance in different ash and gas conditions is known prior to exposure, so that appropriate mitigation techniques can be applied to protect mission critical electronics used within the critical infrastructure sectors and volcanic surveillance operations.

Experiences and recommendations made during and after the eruption of Mount St. Helens in 1980 are influencing much of the volcanic risk mitigation techniques used for electronic equipment today. However, most of the electronic equipment used then is obsolete today and the recommendations are outdated. Gordon *et al*. (2005) updated this work by investigating the vulnerability of late 1990s style desktop computers to laboratory simulated volcanic ashfall. They found that some abrasion occurred on moving parts, such as fan bearings, and short circuits occurred when the ash was moist. The major limitation of this work was that ash with an acidic chemical coating was not used, therefore reducing the potential for the ash to be electrically conductive and corrosive when wet. This thesis will consider 21st century technology by focusing on quantifying the vulnerability of modern laptop computers to both volcanic ash and gas hazards. Laptops are very common in all aspects of society, including critical infrastructure sectors and volcanic surveillance operations, and due to their portability they have a higher risk of exposure to volcanic ash and gas. Exposure of laptops to volcanic hazards is likely to increase over time as they become more popular, with an increasing reliance on connectivity, data storage and sharing and as society develops and expands into volcanically active areas. It is therefore important that the risk posed to laptops from volcanic ash and gas hazards, be reduced through risk management.

1.1.1. Risk Management Framework

The risk management framework has been developed to provide a systematic and logical way to reduce risk through: risk identification; risk analysis; risk evaluation; and risk reduction (Blong, 2000; Standards New Zealand, 2009) (Figure 1.1). In volcanology, this framework provides a common guideline for all the different organisations and research groups to undertake effective risk management and ultimately risk reduction. As such, this thesis will use this framework to undertake vulnerability assessments for laptop computers subjected to volcanic ash and gas hazards.

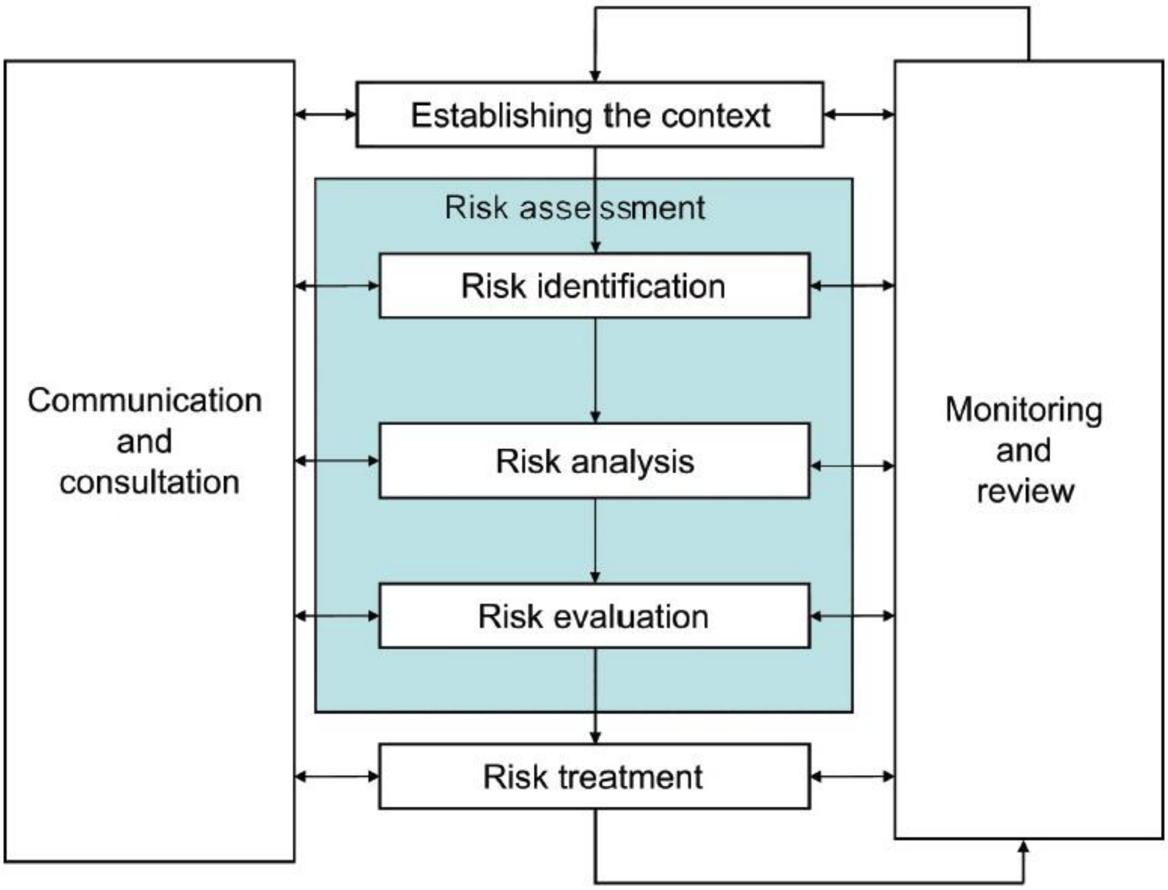

Figure 1.1: Risk management framework (from Standards New Zealand, 2009).

The following equation defines terms used in the risk management process (Blong, 2000):

$$Hazard \times Vulnerability = Risk$$

Hazard is defined as the interaction between society and an extreme natural event (e.g. volcanic eruption) with the potential to cause loss of life and infrastructure damage. Vulnerability is the degree to which elements (e.g. people, infrastructure, etc.) can be damaged due to exposure to the hazard. Risk is the probability that damage to elements will occur as a result of the hazard.

After establishing the context and objectives, the risk management process moves into the risk identification step. In the context of this thesis, this step involves identifying all potential volcanic hazards within a certain area and characterising their impacts. In addition, all the elements (e.g. people, buildings, critical infrastructure, etc.) at risk from the hazard need to be identified. It is also important to know how the elements relate spatially and temporally to the hazard and their potential vulnerabilities (Crozier and Glade, 2005). Identification is achieved through reviewing previous hazards that have occurred in the study area, from literature and geologic investigations (Kaye, 2008). This step essentially identifies all the factors that need further investigation in the risk analysis stage (Crozier and Glade, 2005).

The risk analysis and evaluation stages are focused on developing an understanding of the risks (Standards New Zealand, 2009) so they can be compared and ranked. This involves assessing the magnitude and frequency of volcanic hazards and the vulnerabilities of exposed elements. These assessments are either deterministic or probabilistic or a combination of both.

Deterministic scenario based assessments use hypothetical eruption scenarios, based on previous eruption data, to determine the impact of volcanic hazards on the elements. These generally focus on worst-case scenarios and provide a ‘it will occur/it will not occur’ type answer (Haneberg, 2000). These assessments have several limitations such as: subjective judgments by experts resulting in uncertainty of risks; focusing only on one scenario at a time; and not quantifying the likelihood of the risks (Kaye, 2008). These limitations can be overcome by moving towards probabilistic risk assessments.

Probabilistic risk assessments are used to determine the probability of a hazard occurring and its associated damage from a range of scenarios, with limited subjective input. These assessments are better at handling a range of hazards, magnitudes and variable hazard frequency/return periods. An example of this type of assessment is a Bayesian Event Tree (BET). In this assessment all potential volcanic scenarios are mapped out with corresponding probabilities of occurrence (Newhall and Hoblitt, 2002; Kaye, 2008). A BET illustrates the likelihood of all possible events and typical damage that will occur. To determine the degree of damage that can occur in each scenario, fragility functions can be incorporated into probabilistic risk assessment.

Volcanic fragility functions are probabilistic functions which relate the amount of element damage, or vulnerability, to hazard intensity (e.g. ashfall thickness, pyroclastic density currents velocity, etc.). These functions are developed through the observation, either in the field or in a controlled laboratory environment, of critical elements under a range of volcanic impact conditions and a numerical relationship defined which best estimates the fragility distribution. They are helpful during risk reduction, as it can be seen under which conditions damage or disruption can occur and where mitigation techniques may help reduce damage and therefore risk. These functions are developed within the newly emerging field of volcano engineering.

Volcano engineering is similar to earthquake engineering and is focused on determining quantitative vulnerability of critical components, to a range of volcanic hazards. As volcano engineering is an emerging field, limited quantitative vulnerability data exists. However, this is being addressed by various research groups including the Volcanic Ash Fall Impacts Working Group (Wilson *et al.*, 2011, *in press*) which is part of the International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI).

The final step in the risk management process is risk reduction. This step is aimed at how to best reduce the hazard and/or the vulnerability of the elements within the affected area. In volcanology, reduction of hazards is not always possible and in most cases is very difficult, as they are naturally occurring events that are not easily controlled by humans. Therefore, it is more beneficial to focus risk reduction efforts on reducing the vulnerability of exposed elements. This can be achieved in a number of ways. Firstly, and most importantly, vulnerability can be reduced by the implementation of various mitigation techniques/actions/behaviours, developed through the integration of field and laboratory analysis. These techniques can protect certain elements from impacts caused by volcanic hazards. Secondly, through intensive volcanic surveillance, which may provide data about impending eruptions. This may lead to the evacuation of communities thereby reducing their risk (Tilling, 2008). Lastly, through educating and communicating with the community about the hazards and associated risks they may face during an eruption (Blong, 1996), and providing information about how they can best reduce their personal vulnerability to volcanic hazards.

1.2. Aims and Objectives

The goal of this research is to assess the vulnerability of laptop computers to volcanic ash and gas hazards, through field and laboratory based experiments.

The objectives for this research are:

- To determine the vulnerability of laptop computers and componentry to volcanic ash and gas.
- To understand if and how damage to electronic equipment, caused by volcanic ash and gas, impacts critical infrastructure sectors.
- To provide volcanic observatories and the wider volcanology and critical infrastructure community with appropriate mitigation options to reduce the risk to electronic equipment from impacts caused by volcanic ash and gas.

1.3. Research Methodology

The research methodology used in this thesis follows the risk management process of risk identification, analysis and reduction.

The risk identification process was undertaken in two parts:

Firstly, a literature review of the formation, dispersal and properties of volcanic ash and gas was undertaken, to give insight into how the ash and gas hazards develops and what the likely impacts are (Chapter Two).

Secondly, online questionnaires were used to gather first hand data of volcanic ash and gas damage to electronic equipment (Chapter Three). One questionnaire was for members of the World Organization of Volcano Observatories (WOVO) and was used to establish which volcanic hazards have affected their surveillance equipment and to what extent. The other questionnaire was directed at businesses in Rotorua, New Zealand, to investigate impacts of long term geothermal gas exposure on their computers.

Risk analysis was also undertaken in two parts:

Firstly, vulnerability of laptop computers to volcanic ash was analysed through laboratory based experiments (Chapter Five). In these experiments, laptop computers were exposed to various simulated volcanic ashfall conditions. This allowed the development of vulnerability functions for laptop functionality against ash grain size and accumulation rate (Chapter Seven).

Secondly, two field based gas vulnerability experiments were undertaken at White Island, New Zealand, to assess the vulnerability of laptop computers to volcanic gases (Chapter Six). These experiments allowed the development of a scenario based event tree and risk table for laptop exposure to volcanic gas (Chapter Seven).

Completing the risk management process, various mitigation techniques were considered in order to reduce the overall vulnerability of laptop computers to volcanic ash and gas (Chapter Five). These mitigation techniques may need to be refined, through the risk management review process, in the coming years as new computer technology is developed.

Chapter Two – Literature Review

2.1. Introduction

The purpose of this literature review is to understand how volcanic ash and gas are formed; their dispersal in the environment; their physical and chemical properties; and how they impact on critical infrastructure. This is part of the risk identification stage within the risk management framework.

2.2. Volcanic Ash

2.2.1. Formation of Volcanic Ash

Volcanic ash is the product of explosive volcanic eruptions. The forces associated with magmatic gas expansion and release during magma ascent, shatters the magma into small fragments that are injected into the atmosphere. Ash is formed in the following scenarios.

2.2.1.1. Magmatic Eruptions

Prior to magmatic eruptions, magma rises up the volcanic conduit, as it does volatiles, primarily water (H_2O) and carbon dioxide (CO_2), in the magma exsolve to form gas bubbles. With further decompression the bubbles grow, the rate of which is governed by: the decompression rate; the deformation rate of magma; the volatile diffusion rate (Lensky *et al.*, 2004); and the proximity to neighbouring bubbles (Cashman *et al.*, 2000). As more bubbles nucleate and grow, a foam layer is produced, which decreases the density of the magma, accelerating it up the conduit. Fragmentation is thought to occur when bubbles occupy ~70-80 vol% of the erupting mixture (Cashman *et al.*, 2000) and can result from high strain rates in the magma/bubble mixture or from the failure of bubble walls (Gardner *et al.*, 1996; Papale, 1999; Cashman *et al.*, 2000; Gonnermann and Manga, 2003; Lensky *et al.*, 2004; Namiki and Manga, 2008). When fragmentation occurs, the magma transforms from a liquid with suspended bubbles to a gas with suspended particles (Cashman *et al.*, 2000), causing a reduction in density, which accelerates the gas mixture out of the conduit to form an eruptive plume (Figure 2.1).

2.2.1.2. Phreatomagmatic Eruptions

The rise of magma during phreatomagmatic eruptions is the same as for magmatic eruptions, however, eruption is caused when magma comes into contact with surface water, groundwater, snow or ice. Driving these eruptions is the efficient conversion of thermal energy, in the magma, into mechanical energy (fragmentation) (Austin-Erickson *et al.*, 2008). As magma, which is significantly hotter than the boiling point of water, comes into contact with water, an insulating vapour film forms (Leidenfrost phenomenon) (Zimanowski *et al.*, 1991; Morrissey *et al.*, 2000; Zimanowski, 2000). This vapour film will eventually collapse due to an external trigger (e.g. seismic shocks) or local implosions (Morrissey *et al.*, 2000; Zimanowski, 2000), resulting in thermal and mechanical coupling (i.e. direct contact) of cold water and hot magma (Zimanowski, 2000). This increases the heat transfer from the magma to the water by 1-2 orders of magnitude (Zimanowski, 2000), leading to the rapid expansion of superheated, pressurised water, which in turn causes a rapid increase in load on the magma, leading to brittle deformation and explosive fragmentation (Morrissey *et al.*, 2000). Fragmentation causes an increase in contact area between magma and water creating a feedback mechanism (Zimanowski, 2000), leading to further fragmentation and production of fine ash particles. Finally the superheated water vaporises (Zimanowski, 2000), ejecting magma fragments and steam out of the conduit.

2.2.1.3. Lava Dome Collapse

Volcanic ash may also be produced by rapid decompression of viscous lava domes during collapse. Soon after dome extrusion, the outer layer cools down and becomes a highly viscous barrier preventing volatiles from escaping, thereby allowing pressure to build inside the dome. If the cap is removed by an external force (e.g. gravitational collapse of the dome) the pressure inside the dome will drop rapidly, leading to fragmentation of the dome material, provided the dome is of a high enough viscosity that it behaves in a brittle manner when deformed (Alidibirov and Dingwell, 2000).

The following three fragmentation mechanisms are recognised by Alidibirov and Dingwell (2000): (1) unloading elastic wave propagation; (2) layer-by-layer fragmentation; and (3) rapid gas-filtration flow. These three situations are very similar to what happens during magmatic eruptions. As the cap rock is removed pressure is released and a fragmentation wave can propagate down through the dome causing any gas bubble to expand, fragmenting the lava. After dome fragmentation occurs, the pyroclastic material is transported as a pyroclastic density current (Parfitt and Wilson, 2008).

2.2.1.4. Abrasion and Secondary Fragmentation in Pyroclastic Density Currents

Pyroclastic density currents are fast-moving, ground-hugging, liquid like flows of hot tephra particles and gas (Parfitt and Wilson, 2008), which travel down the flanks of volcanoes and form ignimbrite deposits (Freundt *et al.*, 2000). They can be formed by: the collapse of eruption columns or by the collapse of viscous lava domes (Parfitt and Wilson, 2008) (see Section 2.2.1.3 for an explanation of the latter). If an eruption column becomes unstable because the bulk density of the plume is greater than that of the surrounding atmosphere, due to limited entrainment of air, the column will collapse (Parfitt and Wilson, 2008). As the column collapses, particles will fall and move down the flanks of the volcano as a pyroclastic density current.

Within pyroclastic density currents, particles can collide to produce finer grained particles. In addition, secondary fragmentation can occur in pumice fragments, due to the conservation of heat within the flows (Walker, 1981). These two processes can produce large quantities of very fine grained ash, commonly 20% is finer than 20 μm (Walker, 1981). This ash is removed from the flow to form co-ignimbrite ash plumes.

2.2.2. Dispersal of Volcanic Ash

Volcanic ash can be transported away from volcanoes in two different ways: in a convective eruption plume; and/or in a pyroclastic density current and associated co-ignimbrite plume.

2.2.2.1. Convective Eruption Plumes

A convective eruption plume is formed right after fragmentation as pyroclasts and gas are ejected, at high velocity, out of the conduit and into the atmosphere. The first region of the volcanic plume is the jet thrust zone (Figure 2.1) where the bulk density is greater than that of the surrounding atmosphere and the rise of the plume is due to the momentum from the explosion (Carey and Bursik, 2000; Parfitt and Wilson, 2008). As air is drawn into the jet thrust zone by turbulent eddies (a process called entrainment), both bulk density and velocity decrease, with the transition into the convective zone (Figure 2.1) occurring when the bulk density of the plume is less than that of the surrounding atmosphere (Carey and Bursik, 2000). Upward motion in this zone is controlled by thermal buoyancy (Parfitt and Wilson, 2008). At a height where the bulk density of the plume and surrounding atmosphere are the same (the umbrella zone, Figure 2.1), the plume will cease rising and will start moving laterally (Carey and Bursik, 2000; Parfitt and Wilson, 2008), sometimes up to thousands of kilometres (USGS website, 2010b; Wilson *et al.*, 2011, *in press*).

Ash fallout occurs in three stages (Rose *et al.*, 2001). In the first stage, coarse ash falls out close to the source within the first 1-2 hours after eruption. During the second stage, which can last for up to 24 hours, fine and very fine grained particle concentration within the plume decreases rapidly through particle aggregation. Aggregation occurs by electrostatic attraction of ash particles (Gilbert *et al.*, 1991; James *et al.*, 2002) and/or by combining of ash particles with water (Gilbert and Lane, 1994; Textor *et al.*, 2006; Durant and Rose, 2009). During the last stage, fallout is less concentrated, as the plume moves thousands of kilometres downwind of the source. These stages produce ashfall deposits which generally decrease in thickness and grain size with increasing distance from the vent (Blong, 1984; Parfitt and Wilson, 2008; USGS website, 2010b). However, fine ash particles may remain in the umbrella zone for long periods of time (days to weeks) due to turbulence in the plume (Parfitt and Wilson, 2008), and can have an impact on global climate and the aviation industry.

Phreatomagmatic eruption plumes are similar to magmatic eruption plumes in most respects. However, due to the high concentration of steam involved in a phreatomagmatic eruption, the plume will be less buoyant due to the cooling effect of the steam, and will therefore not rise as high as a magmatic eruption plume. Also aggregation of ash by interaction with water, forming accretionary lapilli, will be more prevalent in these plumes.

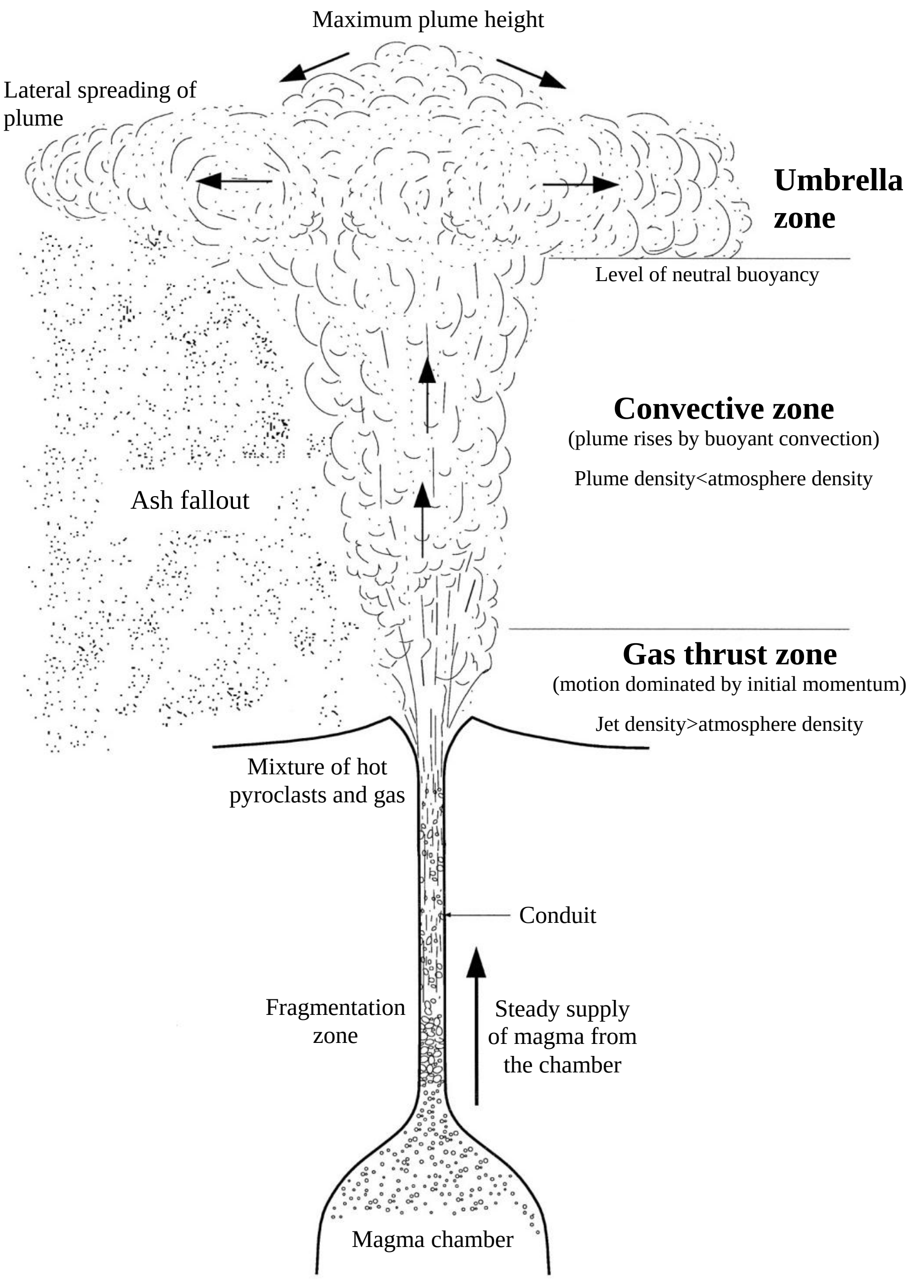

Figure 2.1: Formation of an eruption plume by fragmentation of silicic magma. As pyroclasts leave the vent a plume forms, which has three distinct zones: gas thrust zone; convective zone; and the umbrella zone (modified from Carey and Bursik, 2000).

In addition to ash, eruption plumes also contain large quantities of gases such as H_2O, sulfur dioxide (SO_2), hydrogen sulfide (H_2S), carbon monoxide (CO) and hydrogen chloride (HCl) (Witham *et al.*, 2005) and volatile elements such as sulfate (SO_4^{2-}), chlorine (Cl) and fluorine (F) (Jones and Gislason, 2008). These gases and volatiles are scavenged by the ash particles and adsorbed onto their surfaces, producing acid surface coatings (Witham *et al.*, 2005; Stewart *et al.*, 2006; Delmelle *et al.*, 2007). Dissolution reactions then occur between the ash's silicate constituents and the acid coating, producing sulfate and halide salts which are commonly found on the surface of ash particles (see Section 2.2.3.6) (Rose, 1977; Delmelle *et al.*, 2007).

2.2.2.2. Pyroclastic Density Currents

Co-ignimbrite plumes can form from the buoyant rise of gas and particles from the top of pyroclastic density currents (Carey and Bursik, 2000). As the pyroclastic density current travels away from the source, modifications of the physical properties of the flow occur. Smaller particles are removed from the flow by elutriation and form a less dense zone overlying the main flow (Carey and Bursik, 2000). The hot, less dense zone then entrains the surrounding air and a buoyant co-ignimbrite plume is formed (Carey and Bursik, 2000; Parfitt and Wilson, 2008), which will be dispersed by the wind. Co-ignimbrite plumes tend to have higher concentrations of fine ash particles compared to magmatic eruption plumes (Dartevelle *et al.*, 2002; Rose and Durant, 2009) due to abrasion in the pyroclastic density current (see Section 2.2.1.4).

2.2.3. Properties of Volcanic Ash

Physical and chemical properties of volcanic ash vary greatly with different magma and gas compositions, eruption styles, durations, intensities and atmospheric conditions. However, it is important to understand all of the properties as they influence how volcanic ash can impact upon a large range of critical infrastructure sectors. The following is a summary of the general properties of volcanic ash.

2.2.3.1. Grain Size

Volcanic ash is defined to be any particles (pyroclasts) with diameters <2 mm (Rose and Durant, 2009), and can be as fine as 1 μm (USGS website, 2010b). The overall grain size distribution of ash can vary greatly due to magma composition. Rhyolitic magmas generally produce finer grained material compared to basaltic magams, due to its higher viscosity, which promotes highly explosive eruptions. Grain size can also vary at different locations around the source. This is controlled by atmospheric conditions at the time of the eruption.

2.2.3.2. Composition

Volcanic ash is composed of vitric (glass), crystal and lithic particles. Vitric particles are high in silica and are derived from the molten part of the magma, which rapidly cools during eruption (USGS website, 2010b). Crystal fragments are derived from phenocrysts within the magma. Different crystals reflect differences in magma composition (Johnston, 1997). Lithic particles are derived from rocks within the volcanic vent and may or may not be magmatic in origin. Overall composition can range from high (>63 wt%) to low (<55 wt%) silica, as a result of magma composition.

2.2.3.3. Morphology

Volcanic ash can form a number of different irregular shapes and textures, which are controlled by eruption type, magma composition, volatile content and transportation history (Heiken, 1972). Volcanic ash is commonly filled with vesicles (Figure 2.2) which result from volatile release during magma ascent. These vesicles can control the shape of glass particles (Heiken, 1972), as some glass particles are fragments of vesicle walls. Vesicles also increase the surface area of the particles allowing a greater quantity of soluble salts to be attached to particles. Volcanic ash can also have a blocky morphology. This generally occurs during phreatomagmatic eruptions, due to stresses within the quenched magma (Heiken, 1972).

During ash transport, the particles may aggregate forming large clusters of particles. Particles may also be abraded during transport by contact with other particles, giving ash a rounded morphology.

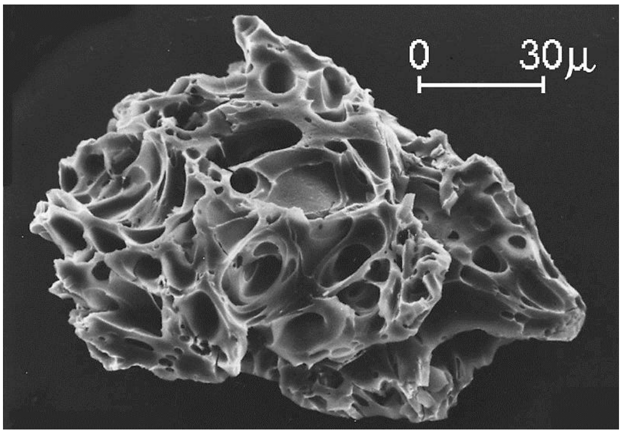

Figure 2.2: Vesiculated glass shard from the 18 May 1980 Mount St. Helens eruption (from USGS website, 2010b).

2.2.3.4. Abrasiveness

Volcanic ash is known to be an abrasive material due to particle shape (e.g. angular edges on glass shards) and hardness. The hardness of individual particles ranges from Moh's hardness of two for mica to seven for quartz, with glass having a hardness of 5-6 (USGS website, 2010b), the same as steel.

Abrasion can be classed as: two body abrasion; three body abrasion; and erosion (Gordon *et al.*, 2005). Two body abrasion occurs when particles become imbedded into a surface which abrades against another. In three body abrasion the particles are able to move freely between two surfaces, abrading both of them. Erosion occurs when particles impact a surface at high speed (e.g. leading edges on aircraft). Currently there is little quantitative data available for two and three body abrasion caused by volcanic ash (Broom, 2010) as the majority of work to date has been related to erosion of aircraft surfaces after flying through volcanic ash plumes (Gordon *et al.*, 2005). However, this an important parameter to understand as many infrastructure sectors have equipment with moving parts (e.g. water pumps, motors, air conditioning systems, switching gear, etc.) which can be abraded by volcanic ash.

2.2.3.5. Density

Volcanic ash particle density and bulk density are highly variable and dependant on grain size, composition, particle shape, moisture content, etc. Densities can vary from 700 kg/m^3 for pumice to 3,200 kg/m^3 for mafic crystals (USGS website, 2010b). Bulk densities range from 500-1,500 kg/m^3 for dry ash deposits and from 1,000-2,000 kg/m^3 for wet deposits (USGS website, 2010b). These differences in density will affect how and where particles are deposited, with lower density particles (glass and pumice) deposited further away from the source than denser particles. Density is also important for building load impacts.

2.2.3.6. Soluble Surface Coating

During volcanic eruptions, ash particles scavenge magmatic volatiles within the plume, forming a coating of soluble salts and mineral acids on the ash surface. The most common of salts are sodium chloride (NaCl) and calcium sulfate ($CaSO_4$) (Witham *et al.*, 2005). Acids include, sulfuric acid (H_2SO_4), HCl and hydrogen fluoride (HF) (Stewart *et al.*, 2006). The scavenging mechanism is not well understood (Witham *et al.*, 2005), but is likely to be from absorption of aerosols onto ash particles (Óskarsson, 1980) and acid controlled dissolution of silicate glass and minerals, followed by precipitation at the ash-liquid interface (Delmelle *et al.*, 2007).

The concentration and type of soluble salts present on ash particles is controlled by magma and gas composition, the style of eruption and ash morphology. Eruption style can influence soluble salt content, as larger eruption plumes from magmatic eruptions generally allow greater mixing between ash and gas (Witham *et al.*, 2005). Eruptions through crater lakes and hydrothermal systems can alter soluble salt content, as ash particles can mix with elements in these systems (e.g. Cronin *et al.*, 1998). Ash morphology is a major factor in control soluble salt content. Highly vesicular particles have large surface areas, which allows a greater concentration of soluble salts to be absorbed onto their surfaces (Witham *et al.*, 2005).

When ash particles mix with water, dissolution of the soluble components occurs, in some very cases rapidly (Gislason *et al.*, 2011). Some salts may also deliquesce (dissolution by absorbing moisture from air) if the relative humidity is high (Cole *et al.*, 2011). The major species found within ash leachates are: sodium (Na^+); calcium (Ca^{2+}); magnesium (Mg^{2+}); chloride (Cl^-); fluoride (F^-); and SO_4^{-2}, in addition to another 49 species that have been found (Witham *et al.*, 2005). These species can impact upon bodies of water through acidification, and by increasing the concentration of toxic elements, like F^- (Stewart *et al.*, 2006). In addition, ash may also be corrosive to metal due to the acidic nature of the leachate. The process of corrosion cause by ash is similar to that caused by gas, outlined in Section 2.3.2, where the acidic ash leachate acts as the electrolyte.

2.2.3.7. Conductivity

When dry, volcanic ash is highly resistant to the flow of electric current, due to the solid nature of the soluble salts, which act as insulators, however when ash is wetted it becomes conductive (Wardman *et al.*, 2010). This is because the salts dissolve, providing a pathway for electrons to flow. A recent study by Wardman *et al*. (2011, *in press*) concluded that conductivity of volcanic ash will increase with: increasing moisture content; increasing soluble salt content; and increasing compaction, as these parameters increase the pathways available for electron flow. Grain size alone did not have a major influence on ash conductivity, as all grain sizes tested showed similar conductivities.

2.2.4. Volcanic Ash Impacts to Critical Infrastructure

Volcanic ash is the most widely distributed product from explosive volcanic eruptions (Stewart *et al.*, 2006; Wilson *et al.*, 2011, *in press*). It can therefore pose a significant risk to a wide range of critical infrastructure (water supply, electricity networks, wastewater systems, land and air transport, etc.), including vital components (electronics and air conditioning), which can reduce societies' ability to cope with disaster. Many authors have undertaken research into how various infrastructure components are impacted by volcanic ash, a selection of these studies is shown in Table 2.1.

Table 2.1: A selection of relevant research papers focusing on volcanic ash impacts on critical infrastructure.

Critical Infrastructure	**Impacts**	**References**
Electricity Networks	• Insulator flashover due to low resistivity of wet ash • Line breakage due to ash accumulation and adherence • Damage to substations	Nellis and Hendrix, 1980; Sarkinen and Wiitala, 1981; Stember and Bastiste, 1981; Blong, 1984; Heiken *et al.*, 1995; Johnston, 1997; Durand *et al.*, 2001; Wilson *et al.*, 2009; USGS website, 2010; Wardman *et al.*, 2010; Wilson *et al.*, 2011, *in press*.
Water Supplies	• Pipes become blocked with ash • Filters are quickly blocked by ash • Accelerated wear of pumps from ash laden water • Acidic surface coating on ash can degrade water quality • Ash can increase water turbidity reducing the effectiveness of water treatment	Blong, 1984; Johnston, 1997; Durand *et al.*, 2001; Cronin *et al.*, 2003; Stewart *et al.*, 2006; Stewart *et al.*, 2009a; Stewart *et al.*, 2009b; USGS website, 2010; Wilson *et al.*, 2010a; Wilson *et al.*, 2010b; Wilson *et al.*, 2011, *in press*.
Wastewater Networks	• See water supplies above • Ash can impede biological breakdown requiring additional chemicals to be used	Day and Fisher, 1980; Blong, 1984; Jonhston, 1997; Durand *et al.*, 2001; Barnard, 2009; USGS website, 2010; Wilson *et al.*, 2011, *in press*.
Transportation Networks	• Reduction in visibility and traction during ashfall • Remobilisation of ash by vehicles further reduces visibility	Blong, 1984; Casadevall, 1994; Casadevall *et al.*, 1996; Johnston, 1997; Durand *et al.*, 2001; Johnston *et al.*, 2001; Barnard, 2009; Guffanti *et al.*,

	• Moving parts of vehicles are vulnerable to abrasion • Leading edges, windscreens, pitot tubes and engines of aircraft are vulnerable to abrasion • Low concentrations of volcanic ash can close airspace	2009; Guffanti *et al.*, 2010; Sammonds *et al.*, 2010; USGS website, 2010; Wilson *et al.*, 2011, *in press*.
Telecommunication Networks	• Damage to air conditioning systems within exchanges and roadside cabinets • Above ground line breakages	Blong, 1984; Johnston, 1997; Durand *et al.*, 2001; Barnard, 2009; Wilson *et al.*, 2009; USGS website, 2010; Wilson *et al.*, 2011, *in press*.
Air Conditioning Systems	• Reduction in performance and damage due to ash blockages	Barnard, 2009; Wilson *et al.*, 2011, *in press*.
Electronic Equipment	• Potential electrical short circuits and corrosion in the presence of wet ash • Jamming of mechanical components • Loss of functionality during ashfall as equipment is covered with ash	Blong, 1984; Labadie, 1994; Durand *et al.*, 2001; Gordon, 2002; Gordon *et al.*, 2005; Sword-Daniels, 2010; Wilson *et al.*, 2011, *in press*.

2.2.4.1. Volcanic Ash Impacts to Electronic Equipment

A comprehensive literature review has been undertaken on the impacts of volcanic ash on electronic equipment, as it is relevant to the research in this thesis. An explanation of various computer components is provided in Appendix E.

Few instances of impacts to electronic equipment from volcanic ash were reported after the 1980 Mount St. Helens eruption, with damage such as: clogging and jamming of cooling fans;

short circuits; etching of metal surfaces; and overheating due to blocked vents (Blong, 1984; Labadie, 1994; Wilson *et al.*, 2011, *in press*). Electronic equipment has also been damaged indirectly through the failure of air condition systems used to keep the equipment at optimum operating temperatures. In 2007, a number of computers within the Montserrat Volcano Observatory failed due to air conditioning systems becoming blocked with fine ash (Sword-Daniels, 2010).

Due to the lack of data in this area, Gordon *et al.* (2005) conducted experiments with different types of ash (basalt and rhyolite) at different concentrations, to determine the vulnerability of late 1990s desktop computers. They found that computers 'crashed' (restart, shutdown or sustained permanent damage) after 100-150 hours of exposure. All failures occurred when ash particles caused short circuits over the pins on expansion card slots and only during high humidity conditions, when the ash was moist and thus more electrically conductive. However, once the humidity was decreased, the computers continued to operate. They also found that floppy disks were susceptible to ash, with abrasion of the magnetic tape occurring after ~38 hours of exposure. Hard drives were less susceptible and only failed after the breathable environment seal, which lets air pressure equalise between the inside and outside, was removed. After removal, it took ~2 minutes for ash to accumulate under read/write head leading to failure. Overall Gordon *et al.* (2005) found that computers were able to handle ash concentrations up to 219,536 $\mu g/m^3$ without severe problems, except in moist conditions.

Since the experiences of Mount St. Helens, from where most of the electronic equipment mitigation techniques were derived, and the experiments of Gordon *et al.* (2005), computer technology has greatly changed. Equipment has moved away from mechanical components with solid state USB and hard drives, which use flash memory to store data, becoming increasingly popular. Equipment has also become smaller, faster, more powerful and robust with the development of laptop computers, which are designed to be portable while keeping power consumption and heat generation low. Therefore, research in this area needs to be updated to include modern technology, including laptop computers, which has not been considered in previous studies. This thesis aims to do this.

2.3. Volcanic Gas

2.3.1. Formation of Volcanic Gas

Magma contains dissolved gases that can be released to the atmosphere as the magma rises and the pressure decreases. This can occur during volcanic eruptions where gas bubbles fragment the magma, producing ash, which is then ejected by gas and transported in volcanic plumes (see Sections 2.2.1 and 2.2.2). Continuous gas release can also occur through soil, vents, fumaroles and hydrothermal systems (USGS website, 2010a). Gas is released into the atmosphere as acid aerosols, salt particles and compounds attached to ash particles, all of which can travel thousands of kilometres downwind of the source (USGS website, 2010a).

The most abundant gas released into the atmosphere is H_2O vapour followed by CO_2 and SO_2 (Delmelle and Stix, 2000). Also released in smaller quantities are: H_2S; HCl; HF; hydrogen (H_2); and CO (USGS website, 2010a). The concentrations of these gases may change due to variations in pressure and temperature. For example the equilibrium reaction:

$$\mathrm{SO_2 + 3H_2 \Leftrightarrow\ H_2S + 2H_2O}$$

Modelling indicates that this reaction shifts to the right at high pressures, therefore favouring H_2S (Delmelle and Stix, 2000). Cooling of the magmatic gas will also lead to this shift. Conversely, magmatic gases released from a shallow magma body will shift the reaction to the left, favouring SO_2.

Tectonic setting will also influence the type and amount of magmatic gases released. Dissolved gases can be supplied to magma bodies at depth from the mantle, the crust and subducting slabs. Each of these has a distinctive composition which leads to different types of magmatic gases. For example, gases associated with convergent plate volcanoes have higher H_2O and Cl concentrations than divergent and hot spot volcanoes, due to the addition of seawater during subduction (Delmelle and Stix, 2000).

Nonmagmatic process, such as interaction with groundwater, can also cause changes in gas composition. H_2O, SO_2, H_2S and HCl gases will be most affected by nonmagmatic processes (Delmelle and Stix, 2000). For example, SO_2 can react with liquid water (groundwater or atmospheric moisture) to produce H_2SO_4 and H_2S, leading to acid rain (Delmelle and Stix, 2000). SO_2 can also react with H_2O, oxygen (O_2), sunlight and particulate matter in the atmosphere to produce volcanic smog, known as vog (USGS website, 2010a). Vog is a significant hazard in Hawaii, due to the continuous eruptive activity of Kilauea (Hawaiian Volcano Observatory website, 1996).

2.3.2. Volcanic Gas Impacts

Volcanic gases can impact upon human and animal health and the environment due to its toxic nature; however, it can also affect the built environment through corrosion. This has implications for any critical infrastructure sectors located near volcanoes or under eruption plumes, as many buildings and equipment in use could potentially corrode, reducing functionality and causing damage.

Corrosion, by definition, is the process of a metal returning to its natural thermodynamic state (Schweitzer, 2010). Atmospheric corrosion is a complicated electrochemical process which requires the presence of an electrolyte. The most common electrolyte is moisture resulting from rain, fog, dew, high humidity, etc., and it may be acidic, neutral or basic (Schweitzer, 2010). In volcanic environments, gas aerosols which have mixed with H_2O can act as acidic electrolytes. Volcanic ash mixed with H_2O can also act as an electrolyte. Corrosion will occur through various oxidation and reduction reactions, depending on the metal and electrolyte present. Factors such as: relative humidity; temperature; gas type and concentration; rainfall; and orientation of object relative to gas source will affect the amount of corrosion that will occur (Schweitzer, 2010).

Limited quantitative data exists for volcanic gas impacts of critical infrastructure; however, a few studies have investigated corrosion in volcanic environments. Watanabe *et al.* (2006) conducted experiments to determine the level of corrosivity on Miyake Island, Japan after an eruption in 2000. The study was initiated because telecommunication equipment, such as galvanised steel wires supporting communication cables, on the island suffered severe corrosion damage after the eruption. The primary volcanic gases on the island were SO_2 (average concentration of 275 ppb) and H_2S (maximum concentration of 1 ppm). The experiments involved exposing copper (Cu) and silver (Ag) plates to the gases for one and seven months. Results show that various corrosion products (copper and silver oxides, chlorides and sulfides) completely covered the exposed plates within the first month of exposure, quicker than in previous studies. They concluded that telecommunication equipment on the island will need to be checked more frequently to prevent corrosion damage.

Hawthorn *et al.* (2007) undertook a corrosion study of aluminium (Al) on Kilauea volcano, Hawaii in 2006. Al plates were placed downwind of the gas source for one year, to determine if volcanic environments could be a natural accelerated testing facility for corrosion research. Results indicated that corrosion rates of Al in volcanic environments were seven times higher than those in industrial locations in other parts of Hawaii, during the same period. They concluded that Kilauea was a harsh environment for corrosion testing due to the amount of acid rain and Cl^- present.

A study by Durand and Scott (2005) investigated whether volcanic gases (H_2S, CO_2 and radon) were present at elevated concentrations within buildings in Rotorua, New Zealand. The results show that eight out of the nine buildings investigated had detectable concentrations of volcanic gases. The means of gas entry was through the floor, walls and subsurface pipes, even when preventative measures had been taken to prevent gas ingress. They also noted that there was significant corrosion damage to objects that contained Cu such as: electrical systems; computers; telephones; appliances; and water pipes, as a result of H_2S. This was also confirmed by Durand (2006), who undertook a similar study in Rotorua. Durand and Scott (2005) concluded that preventative measures, such as under-floor ventilation systems and under-laying of concrete floors with gas-proof seals, does not always work and the volcanic gas may still enter buildings through the floors and walls and cause damage.

Of relevance to this thesis is the corrosion of electronic equipment. A number of studies have investigated gas corrosion damage to electronic equipment in industrial areas. These areas are known to produce gases that are also found in volcanic environments, such as H_2S and SO_4.

Electronic equipment contains components made from Cu, nickel (Ni), tin (Sn) and Ag which can corrode in the presence of volcanic gases (H_2S, SO_2, HCl, and HF). H_2S will corrode these metals readily at low part per billion concentrations in low relative humidity environments (Muller, 1999). In the presence of moisture and small amounts of chloride compounds, corrosion is greatly accelerated. At concentrations in the low parts per billion range, SO_2 will oxidise metal, protecting it from corrosion, however at higher concentrations and with the combination of moisture, corrosion will occur due to the production of H_2SO_4 (Muller, 1999). HCl will generate Cl^- in the presence of moisture, which will react readily with Cu, Sn, and Ag, corroding it (Muller, 1999). HF is a member of the halogen group and acts like HCl.

Due to the micronisation of electronic equipment even small amounts of corrosion can cause problems and complete failure (Comizzoli *et al.*, 1986; Rivera, 2007). For this reason electronics manufactures protect Cu, Ni, Sn and Ag components by plating them with gold (Au). This does not reduce the component's electrical conductivity but does reduce the corrosion potential, as Au is a noble metal and does not readily corrode. Au will however corrode in the presence of aqua regia, a mixture of three parts concentrated HCl and one part concentrated nitric acid (HNO_3) (Sheng and Etsell, 2007). This has the potential to occur in volcanic environments as HCl is commonly found, and Mather *et al.* (2004) found HNO_3 at four volcanoes in Nicaragua, Italy and Chile.

In addition, the Au plating used is usually 4-8 μm thick, as this provides good protection while remaining cost effective (Muller, 1999). Although, at this thickness Au is usually very porous (Muller, 1999). This porosity allows corrosive gases (H_2S and SO_4) to pass through the Au and corrode the underlying Cu and/or Ni (Krumbein and Antler, 1968; Muller, 1999; Stanley and Muller, 2003; Sun *et al.*, 2007). The corrosion product (copper sulfide or nickel sulfide) is forced back up through the pores to the surface, where it forms a highly resistive coating, causing the component to fail.

Other components inside electronic equipment are made from Cu which are not protected by Au plating, such as Cu heat sinks in computers. These will readily corrode in volcanic environments.

Electronic equipment corrosion could have detrimental effects on all critical infrastructure sectors, during volcanic eruptions, which rely on fully functioning electronic equipment for continued operation. It is therefore important to know how this equipment, particularly computers, operate in volcanic environments and how to best protect them. Hence this thesis.

Chapter Three – Questionnaires

3.1. Introduction

As part of the risk identification stage for this thesis, two questionnaires were undertaken to gather new empirical data as to how electronic equipment is affected by volcanic ash and gas hazards.

One questionnaire was sent to businesses in Rotorua, New Zealand who operate within an active volcanic gas environment and are known to suffer chronic corrosion problems. The other was sent to volcanic observatories who are members of WOVO. These observatories operate in a number of different volcanic environments globally, and can provide valuable insight as to how their surveillance equipment performs in maximum credible exposure conditions.

3.2. Rotorua Questionnaire

Rotorua was chosen because it lies within an active geothermal field within the Rotorua caldera (Durand and Scott, 2005) in the Taupo Volcanic Zone (TVZ), New Zealand (Figure 3.1). The geothermal field covers an area of between 18-28 km^2 (Scott and Mroczek, 2005) and contains rare geysers, mudpools, fumaroles, hot springs and areas of hot barren ground. These are concentrated in urban areas such as: Ohinemutu-Kuirau Park; the Central Business District (CBD); Government Gardens; Ngapuna; Puarenga; Fenton; and Whakarewarewa (Durand and Scott, 2005) (Figure 3.1). Associated with these features is the release of volcanic gases such as CO_2, SO_2 and H_2S, which can cause health problems (Hansell *et al.*, 2006) and damage to electronic equipment (Stanley and Muller, 2003; Durand and Scott, 2005). Durand and Scott (2005) reported significant problems with associated with corrosion and tarnishing of exposed wires and contacts, electronic appliance failure and reliability issues with computers within both residential and commercial buildings in the city.

Businesses were selected as the target audience as they were more likely to have a larger number of computers within their buildings and better maintenance records than residential.

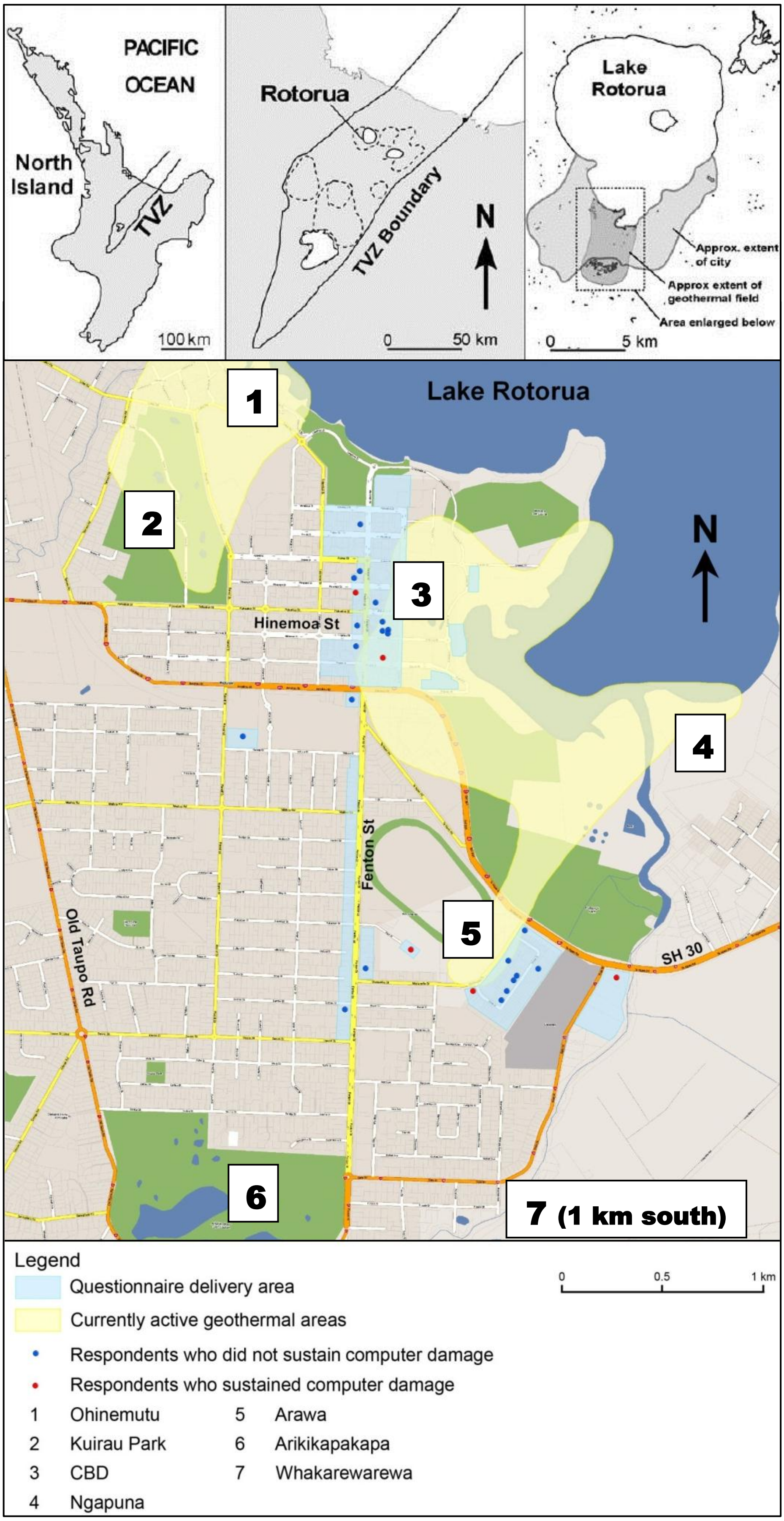

Figure 3.1: Map showing the geography of Rotorua, New Zealand, the questionnaire delivery area, geothermal areas, and where the respondents are located. Top three images from Durand and Scott (2005).

3.2.1. Questionnaire Design and Delivery

The questionnaire contained 45 questions and was developed online using Qualtrics™ Survey Software (Section A.2, Appendix A). The online survey method was chosen as it was the easiest for distribution and had a lower cost associated with it compared to traditional mail-based questionnaires (Smee and Brennan, 2000). Other benefits included: participants not needing to return the questionnaire once complete, as it is submitted online; participants were able to be directed through the questionnaire depending on their previous answers, which meant they did not have to read and respond to questions that did not apply to their situation; and the questionnaire data was able to be directly downloaded, in real-time, and imported into a statistical analysis package. However, a major limitation of online questionnaires is that they generally have a lower return rate than mail-based questionnaires (Kwak and Radler, 2002).

The questions in the questionnaire asked businesses about their location to, and knowledge about geothermal areas; the type of computer damage that had occurred, if any, and if it was related to volcanic gases; and how any damage had affected their day-to-day business activities.

It was difficult to find email addresses for all businesses in the Rotorua area, so an invitation to participate in the questionnaire was hand delivered to 130 businesses on 28-29 June 2010 (Section A.1, Appendix A). The invitation was delivered to every second business on the streets within the highlighted areas in Figure 3.1. This invitation explained the purpose of the project and contained the website address that participants would need to start the questionnaire.

The questionnaire and invitation letter were approved by the Department of Geological Sciences, University of Canterbury, and reviewed and tested by Dr. Thomas Wilson and Professor Jim Cole (supervisors) and Brad Scott (GNS Science) prior to being delivered.

3.2.2. Results

A total of 29 responses were received from the 130 questionnaires that were delivered, giving a response rate of 22%. A brief summary of the results is given below, with the full results given in Section A.3, Appendix A.

3.2.2.1. Proximity to Geothermal Features

Respondents were asked to give the approximate distance to the nearest geothermal feature (e.g. hot barren ground, hot springs, mudpools, fumaroles and geysers). Just under half (n=13, 44%) of the respondents indicated that there was a geothermal feature within 500 m of their property, and 23% (n=3) of those respondents indicated that a geothermal feature was within their businesses' property.

Respondents were also asked if they have had their buildings and/or offices tested for gas. Only 10% (n=3) of the respondents did have gas levels tested, while the remaining respondents said they had not or did not know if gas levels had been tested. This question was then followed up by a question asking the respondents to indicate which gases had been tested. Only one respondent stated that H_2S had been tested, however they did not know the concentration present.

3.2.2.2. Computer Exposure

Respondents generally had more desktop computers than laptop computers within their buildings. All the businesses had at least one desktop computer, with half (n=14) having 1-5. This is compared to a large number (n=10, 37%) of respondents who had no laptop computers. However over half (n=16, 59%) had 1-5 laptops. The most common use for both desktop and laptop computers was general use (n=25 and n=15, respectively) which includes word processing, checking emails, etc. (Figures 3.2 and 3.3).

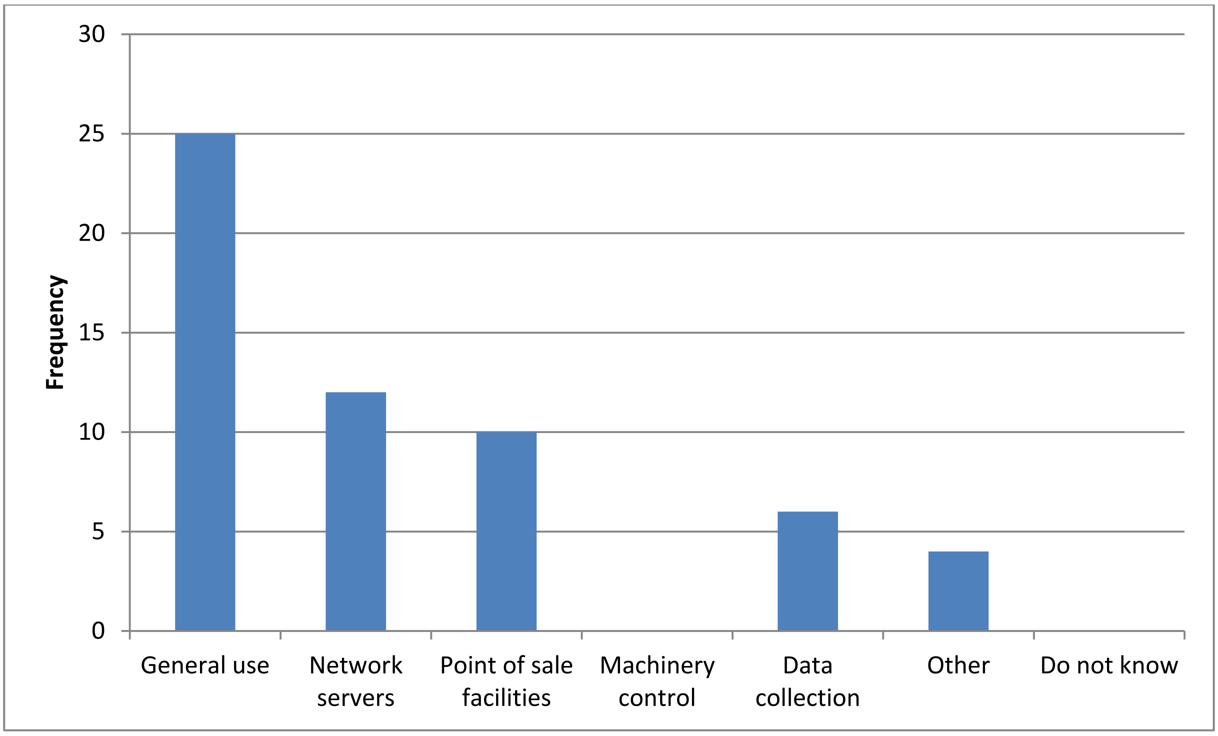

Figure 3.2: Common uses for businesses' desktop computers. Other responses: stock/order (n=1); bookings (via email) (n=1); placing client investment orders (n=1); and internet searches (n=1).

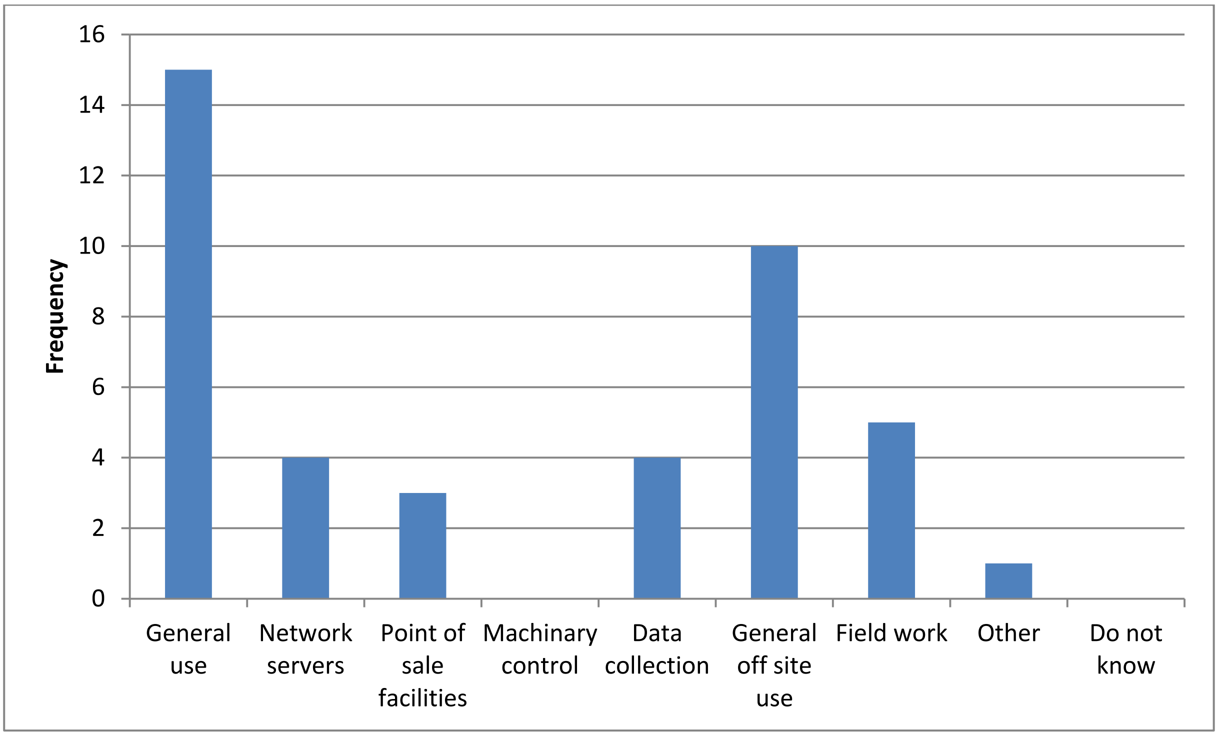

Figure 3.3: Common uses for businesses' laptop computers. Other responses: internet searches (n=1).

The average replacement time of desktop computers ranged from 12-96 months with an average of 42 months. Laptop replacement time ranged from 12-60 months with an average of 36 months. The most common reason for replacing computers was due to poor performance (Figures 3.3 and 3.4).

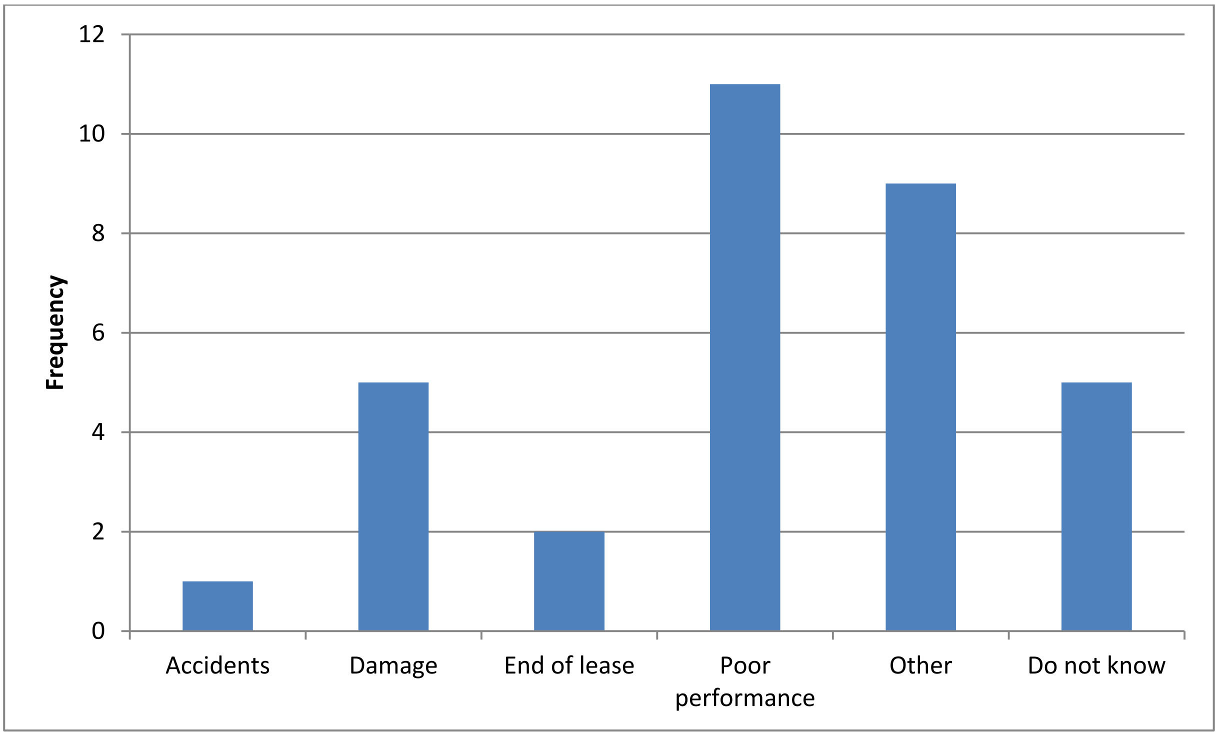

Figure 3.4: Common reasons to replace businesses' desktop computers. Other responses: 'kaput' (n=1); IT department just send a new one (n=1); to keep them high 'spec' (n=1); faults (n=1); wear and tear and malfunctions (n=1); corrosion of circuit boards (n=1); rust due to thermal air (n=1); and end of business life (n=1).

3.2.2.3. Computer Damage

The respondents were asked if any of their computers had sustained damage due to volcanic gases at any time in the past. Less than a quarter (n=5, 19%) of the respondents said their desktop computers had sustained damage from volcanic gases, while 26% (n=7) said damage was not caused by volcanic gases. Over half (n=15, 56%) did not know what had caused the damage. Of the respondents who had laptop computers, none of them reported laptop damage caused by volcanic gases, although over half (n=10, 59%) did not know what had caused the damage.

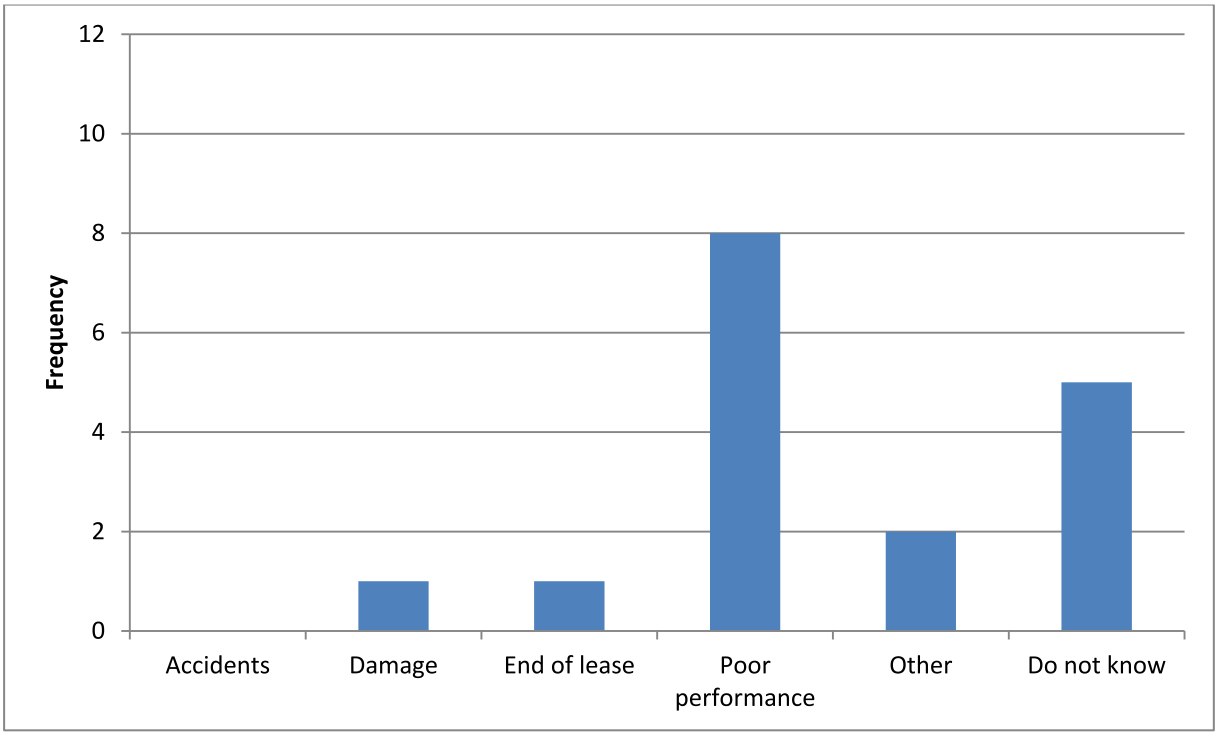

Figure 3.5: Common reasons to replace businesses' laptop computers. Other responses: laptop is fairly new (n=1); and end of business life (n=1).

Of the five respondents who reported desktop computer damage as a result of volcanic gases, one had a geothermal feature within their businesses property and three had geothermal features within 500 m of their property. The other, had a geothermal feature at least 1 km from their building. However, only one respondent was located within the active geothermal field in Rotorua (Figure 3.1).

The most common type of desktop computer damage caused by volcanic gases was the corrosion of the circuit boards, reducing the life expectancy of the computer (n=4) (Table 3.1). This was followed by corrosion of other internal components (e.g. CD drive, hard drive) (n=3) and corrosion of external connectors, reducing the computer's performance (n=3).

The most common impact of this damage was that the respondent's desktop computer would only turn on sometimes (n=4) (Table 3.2). This was followed by the screen only turning on sometimes (n=2) and the keyboard and mouse either working sometimes or not at all. The time taken for this damage to occur ranged from six months to five years, with an average of three years.

Table 3.1: Type of damage sustained by desktop computers due to volcanic gas.

Type of Damage	Count
Corrosion of components on the circuit board reducing life expectancy	4
Corrosion of other internal components reducing life expectancy	3
Corrosion of external connectors reducing performance	3
Corrosion of computer’s external case	0
Corrosion inside power supply reducing life expectancy	0
Corrosion of cooling fans reducing performance	2
Keys on keyboard not responding	1
Mouse not responding	2
Discolouration of screen	1
Acid etching of screen	0
Short circuits	1
Other	0
Do not know	0

Table 3.2: Impacts of damaged desktop computers.

Effect of computer damage	Count
Computer would not turn on	1
Computer would turn on sometimes	4
Computer would turn off periodically without warning	0
Screen would not turn on	1
Screen would turn on sometimes	2
Screen would turn off periodically without warning	0
Keyboard would not work	1
Keyboard would work sometimes	0
Mouse would not work	1
Mouse would work sometimes	1
Loss of data	0
Other	0
Do not know	0

In addition, a number of respondents (n=13, 45%) reported that various other electronic items in their buildings had been damaged by volcanic gas. Items included: televisions; stereos; alarm systems; air conditioning units; and electrical wires.

3.2.2.4. Financial Impacts

The final section of the questionnaire asked respondents a series of financial questions to establish how the damage of computers by volcanic gases affected their business. The questions were separated into planned (foreseeable) and unplanned (unforeseeable) servicing costs for both desktop and laptop computers. Of the five respondents who reported having had desktop computers damaged by volcanic gases, three spent no money on planned servicing costs while the other two spent between <$10,000 per year. However, for unplanned servicing costs, four of respondents spent between <$5,000 per year. The respondents were asked what percentage of the planned and unplanned servicing costs were used as a result of damage to computers from volcanic gas. Two reported that >40% of their planned serving cost per year was used for volcanic gas related damage, while all reported that >30% of their unplanned servicing cost per year was used for volcanic gas related damage.

The respondents were also asked if and how damaged computers affected their business non-financially. The most common answers were loss of time (n=12) and loss of productivity (n=11) (Figure 3.6).

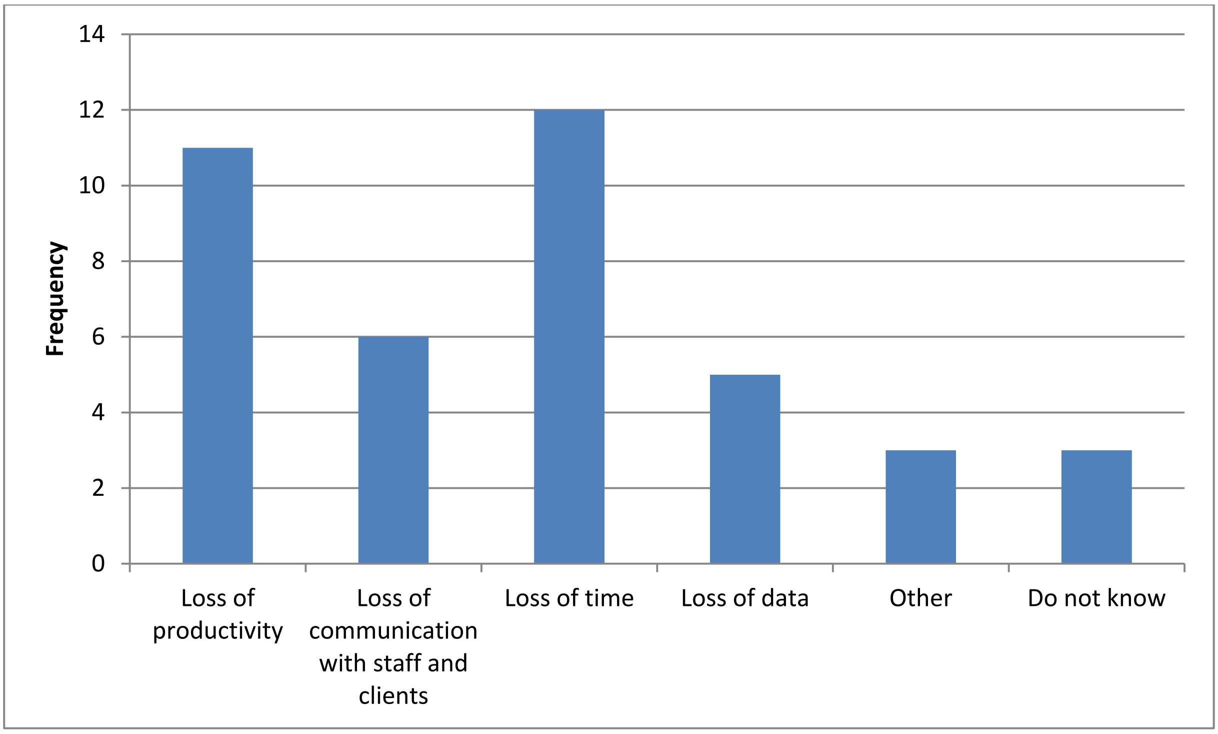

Figure 3.6: The most common non-financial impacts of damaged computers. Other responses: we plan for it so it does not affect us (n=1); inconvenience (n=1); and loss of money from client email hire (n=1).

3.2.3. Discussion and Conclusions

This questionnaire only found a small number (n=5, 19%) of respondents who have had desktop computers damaged by volcanic gases. Most importantly for users of laptop computers (e.g. critical infrastructure sectors and volcanic observatories), there were no reports of laptop damage caused by volcanic gases. It is possible that this could be due to an under reporting of the problem in this questionnaire, as there were a large percentage (56% for desktops and 59% for laptops) of respondents who did not know if their computers had been damaged by volcanic gases. In addition, there were several comments made by businesses during questionnaire delivery, that damaged computers were sent away to be fixed and they do not find out what happened to them.

Laptop computers could also be less likely to be damaged because there were approximately four times more desktop computers in use in Rotorua businesses than laptops. Also the design of laptops compared to desktops may reduce its exposure to volcanic gases, with small cooling fans that turn on only when necessary (i.e. they are not on all the time like desktop computers) which reduces the volume of contaminated air ingested.

For the respondents that reported volcanic gas damage to desktop computers, most of the damage was not major and only reduced the computers reliability (e.g. computer and screen only turning on sometimes). This damage occurred in inconsistent locations around the city, with some occurring at businesses located within the geothermal field, while other damage occurred at locations away from these features (Figure 3.1). The damage also occurred over a large timeframe, 6-60 months. This suggests that volcanic gas related damage to electronics within Rotorua is an acute localised issue. It may depend on proximity to geothermal features, the activity of these features and duration of exposure to volcanic gases. Nevertheless, computer damage may create financial and time costs, albeit minor, for businesses who have to replace damaged computers frequently.

3.3. Volcanic Observatories Questionnaire

Members of WOVO were chosen for the volcanic observatories questionnaire as these organisations operate in a wide range of different volcanic environments. These organisations also spend large amounts of time in the field with sensitive electronic equipment and can therefore provide valuable insights into how this equipment operates in harsh environments. They can also provide information that can inform the design of appropriate mitigation techniques during the risk reduction stage of this thesis.

3.3.1. Questionnaire Design and Delivery

The volcanic observatories questionnaire had 225 questions and was also developed online using Qualtrics™ Survey Software (Section B.3 Appendix B), as this was the easiest method for a questionnaire to be distributed to a range of international organisations. The questions asked about the types of damage that had occurred to volcanic surveillance equipment, laptop computers and solar panels that the organisations operate. It also asked which of the numerous volcanic hazards caused the damage. Questions were also asked about how the organisations protect their electronic equipment from volcanic hazards in order to keep them operational.

Invitations to participate in this questionnaire were emailed to 129 organisations on 16 June 2010 (Section B.1, Appendix B), using email addresses from the WOVO website (www.wovo.org). This invitation explained the purpose of the project and contained the website address that participants would need to start the questionnaire. Reminder emails were sent out on 16 July and 30 August 2010 to participants that had not completed the questionnaire (Section B.2, Appendix B). These emails also contained the website link for the questionnaire.

The questionnaire and invitation letter were approved by the Department of Geological Sciences, University of Canterbury, and reviewed and tested by Dr. Thomas Wilson and Professor Jim Cole (supervisors) and Brad Scott (GNS Science) prior to being emailed.

3.3.2. Results

A total of 19 responses were received from the 129 questionnaires that were emailed, giving a response rate of 15%. Responses came from a number of countries including: Philippines (n=3); Spain (n=3); El Salvador (n=2); Japan (n=2); USA (n=2); Cameroon (n=1); Columbia (n=1); Ecuador (n=1); Italy (n=1), Papua New Guinea (n=1); Trinidad and Tobago (n=1); and Vanuatu (n=1). A brief summary of the results is given below, with the full results given in Section B.4, Appendix B.

3.3.2.1. General Questions

The number of staff members employed at each organisation ranged from <10 to >50, with >50 (n=5, 31%) staff members most common. These organisations monitor a range of different types of volcanoes, including, stratovolcanoes (n=12); calderas (n=10); volcanic fields (n=7); and shield volcanos (n=5). Most observatories (n=9, 64%) monitor between 6-10 volcanoes.

3.3.2.2. Surveillance Equipment

The organisations had a wide range of surveillance equipment with seismic stations being the most common (n=13), followed by global positioning stations (n=11) and remote cameras (n=10) (Figure 3.7). There was also a range of equipment not on the list in the questionnaire, such as magnetometers and thermal imaging equipment. Organisations generally had <5 of each item of equipment, except for seismic stations where some organisations (n=4, 33%) had up to 20 in operation.

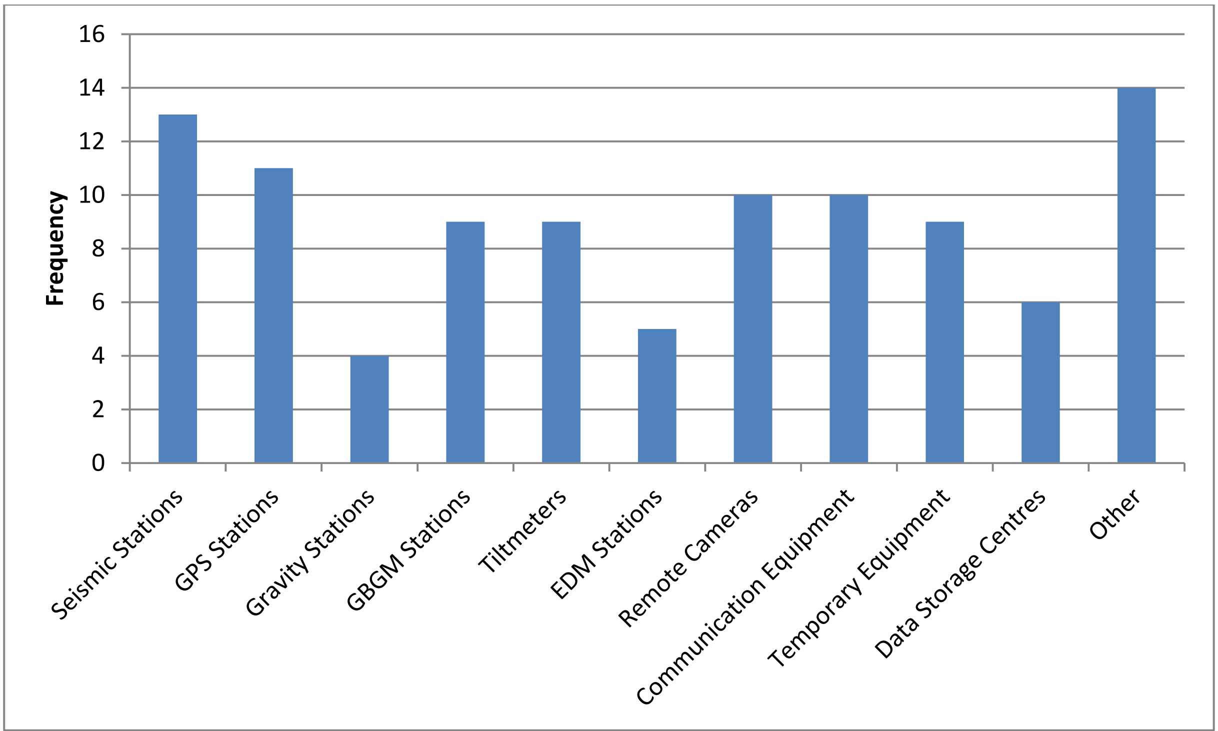

Figure 3.7: Type of equipment used by volcanic observatories for volcanic surveillance. *GBGM Stations: ground based gas monitoring stations; EDM Stations: electronic distance measurement stations.* Other responses: thermometers (n=3); magnetometers (n=2); gas collectors (n=2); self-potential meters (n=1); short level line (n=1); differential optical absorption spectroscopy (n=1); magnetic equipment (n=1); electromagnetic equipment (n=1); infra-red camera (n=1).

The organisations were asked if they took extra effort to protect their volcano surveillance equipment from volcanic hazards, such as ash, gas, acid rain, etc., and 77% (n=10) of them did. Of the three organisations which did not protect their equipment, only one would consider protecting it in the future. The main reasons for not protecting equipment was that any protection would be ineffective and the equipment would not last any longer. The organisations were also asked what volcanic hazard they thought was the most damaging to equipment. Volcanic ash was the most common (n=5, 38%), followed by ballistics (n=4, 31%) (Figure 3.8).

Organisations were asked what materials they use to protect their equipment and how they use these materials to do it. The most common materials used were stainless steel, concrete and Perspex (Figure 3.9). These materials are generally used to construct enclosures around the equipment to provide protection.

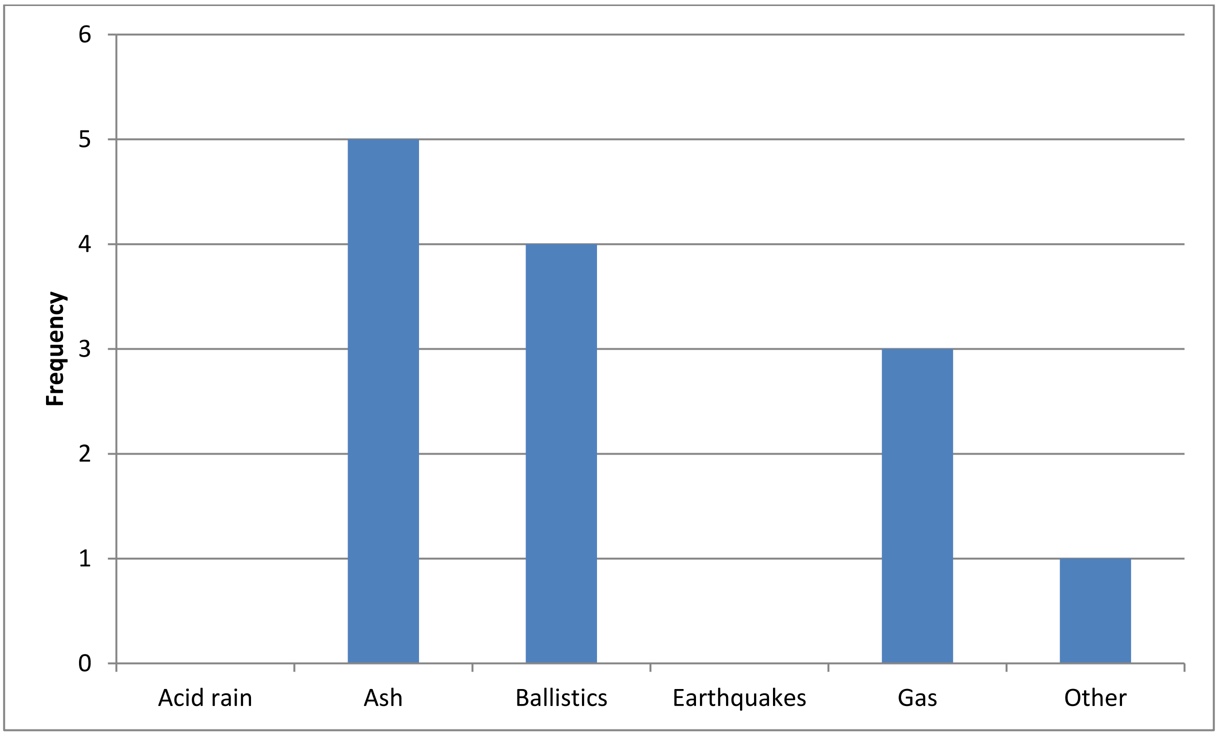

Figure 3.8: Most damaging volcanic hazards to an organisation's volcano surveillance equipment. Other responses: *no comment provided.*

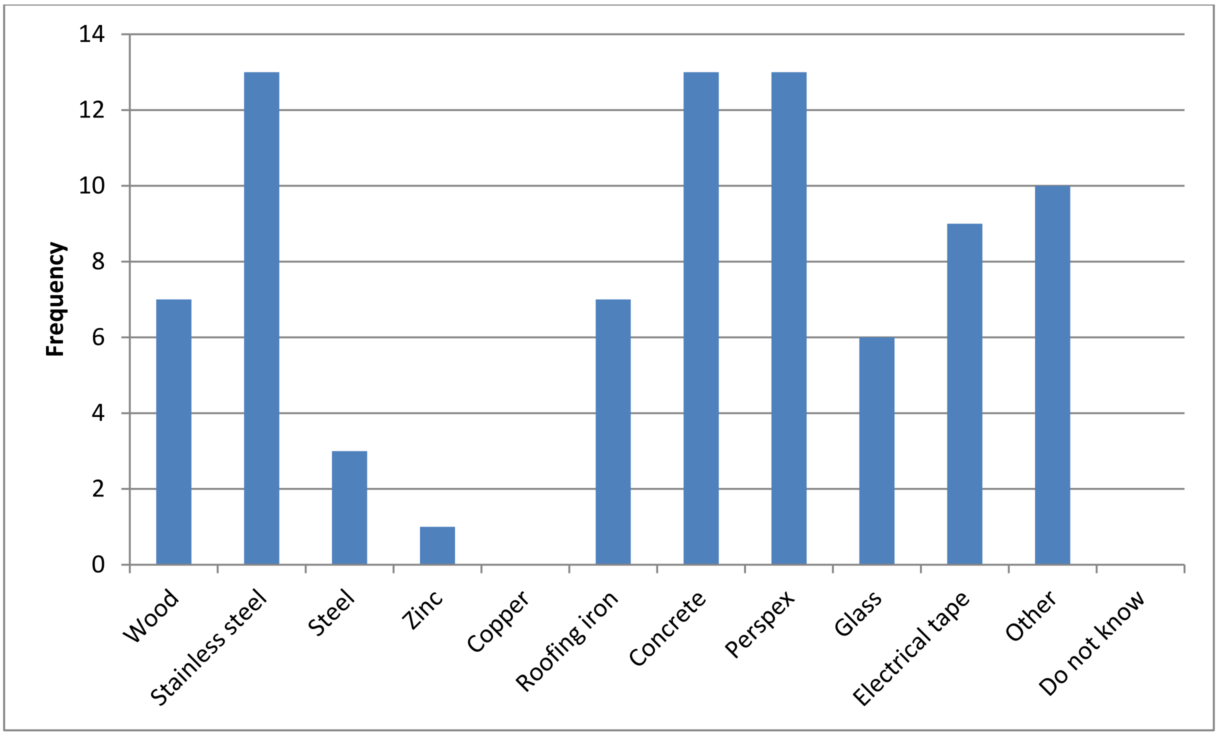

Figure 3.9: Materials commonly used by volcanic observatories to protect their volcanic surveillance equipment. Other responses: aluminium boxes (n=1); tarpaulin (n=1); camera installed inside observatory (n=1); glass used for camera window (n=1); and textile fibres (n=1).

If the organisation protected its surveillance equipment, it was asked if any of this equipment had been damaged by volcanic hazards. The majority (n=22, 65%) of the organisations have had no damage to protected equipment (Table 3.3). Of the respondents who had equipment damaged, the most common type was minor corrosion of the outside of the equipment which did not affect functionality (n=3) and corrosion of components on the circuit boards reducing functionality and life expectancy (n=3) (Table 3.4). There was also some damage caused by non-volcanic hazards such as: animals eating cables, equipment being stolen and water leaking into equipment enclosures.

Table 3.3: Table showing which of an organisation's volcanic surveillance equipment has been damaged by volcanic hazards while being protected.

Equipment	**Has equipment sustained any damage from volcanic hazards?**		
	Yes	**No**	**Do not know**
Seismic stations	4	3	1
GPS stations	1	1	0
Gravity stations	0	2	0
GBGM Stations	0	2	1
Tiltmeters	0	3	0
EDM Stations	0	0	0
Remote cameras	1	3	1
Communication equipment	0	2	1
Temporary equipment	1	3	0
Data storage centres	0	0	0
Other equipment	1	3	0
Total	**8**	**22**	**4**

Table 3.4: Type of damage sustained by volcano surveillance equipment from volcanic hazards. Other responses: chopped cables by animals; stolen equipment; electric and sun overcharge; and water leaks.

Type of damage	**Count**
Minor corrosion of outside of equipment not affecting functionality	3
Major corrosion of outside of equipment reducing functionality and life expectancy	2
Minor abrasion of outside of equipment not affecting functionality	1
Major abrasion of outside of equipment reducing functionality and life expectancy	1
Corrosion of components on circuit boards reducing functionality and life expectancy	3
Short circuits	2
Dents and/or holes from ballistic impacts	0
Acid etching of equipment	2
Clogged motors	1

Clogged air intakes	1
Totally destroyed	0
Other	4
Do not know	1

At the end of each section of questions about a particular piece of surveillance equipment, respondents were asked to rate how effective their protection methods were against various volcanic hazards. Most commonly their protection methods were effective against all hazards (Appendix B). None of the respondents rated their protection methods as ineffective.

3.3.2.3. Laptop Computers

All of the respondents use laptop computers in the field as part of their volcanic surveillance operations. The most common use for them was downloading data from equipment in the field (n=8), followed by configuring equipment in the field (n=6) (Figure 3.10).

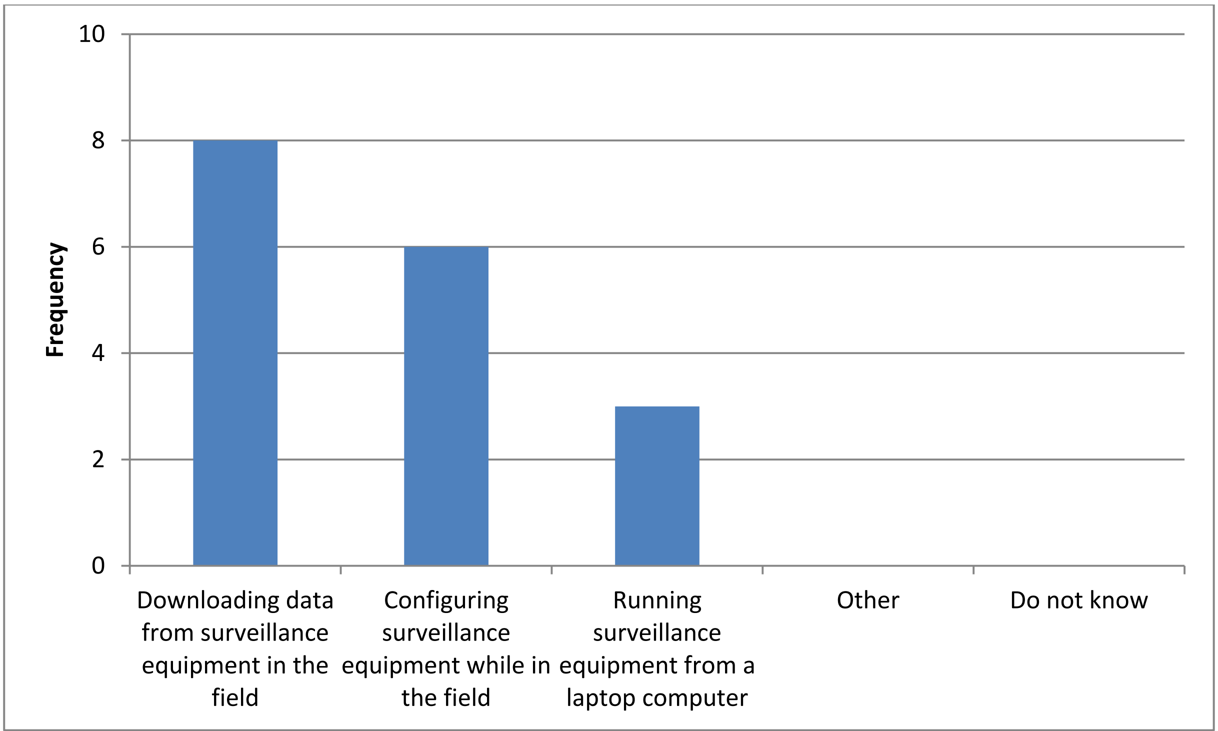

Figure 3.10: Common uses for organisations' laptop computers.

The majority (n=5, 71%) of respondents who use laptops in the field reported that their laptop computers are designed for outdoor use, because they are portable and robust. However, 63% (n=5) of the organisations still provide protection to laptops, if they are taken into the field for more than one day. Protection includes placing laptops inside the same structures the organisations' other surveillance equipment is in and placing laptops inside plastic bags or durable plastic cases.

None of the organisations have had any laptop computers damaged while protected, however one organisation had damage to a laptop computer while unprotected. This organisation reported a range of damage including internal and external corrosion and abrasion of components, clogged air intakes and cooling fans and short circuits. The cause of this damage was reported as volcanic ash and gas.

Less than half (n=3, 38%) of the respondents cleaned their laptop computers when they are returned from the field. Of the respondents that did clean their laptops, they commonly used compressed air and liquid cleaners to do so.

The majority of the respondents (n=5, 71%) indicated that volcanic hazards did reduce the life expectancy of their laptop computers, while 29% (n=2) did not agree with this.

3.3.2.4. Financial Impacts

In the final section of the questionnaire, respondents were asked a series of questions to establish how much of their organisation's budget was used on protecting, repairing and replacing surveillance equipment. Respondents spent <US$30,000 annually on repairing (n=4, 57%) and replacing (n=5, 72%) surveillance equipment. To protect surveillance equipment from being damaged by volcanic hazards, 33% (n=2) of respondents used <10% of their overall surveillance budget, while half (n=3) did not know how much was used.

3.3.3. Discussion and Conclusions

3.3.3.1. Surveillance Equipment

Most of the organisations that responded to this questionnaire did protect their volcanic surveillance equipment, with a range of materials. As such, only a few organisations had suffered damage, from volcanic hazards, to equipment that was protected. It appears the experience of trying to protect equipment in volcanic environments had led to each organisation coming up with the best possible design for their equipment in their situation. In fact, half of the organisations reported they had made changes over time to improve their protection methods. It was also common for organisations to employ different protection methods at different locations around a volcano, as they have learnt that one solution does not fit all applications. This indicates that some impacts from volcanic hazards are localised and can vary depending on location. This is something that needs to be taken into account when designing suitable protection methods for electronic equipment.

3.3.3.2. Laptop Computers

The responses from this questionnaire show that laptop computers are commonly used in various ways as part of routine volcanic surveillance. However, only one respondent indicated that their laptops had sustained damaged from volcanic hazards while in the field. This damage was extensive, affecting a large number of internal and external components. The two hazards that caused this damage were volcanic ash and gas, which is to be expected, as these are very invasive and very difficult to protect against while still maintaining functionality of the laptop. Also these hazards are not usually life threatening to humans, compared with ballistic impacts, so laptops are more likely to be exposed to hazards where humans can operate.

The lack of other reported incidents is because most volcanic observatories take appropriate, yet simple, preventative measures to protect their laptop computers when they are taken into the field. In addition, laptop computers are normally only in the field for 1-2 days and therefore had very limited exposure to volcanic hazards. Some organisations also cleaned their laptops after returning from the field, which would reduce the impact of long term damage such as corrosion from occurring.

Chapter Four – Pseudo Ash Development

4.1. Introduction

In order to conduct volcanic ash vulnerability experiments in the laboratory as part of the risk analysis stage, large quantities of fresh volcanic ash are required. As fresh ash is coated in acidic soluble salts that will cause corrosion, however, these salts are rapidly leached off fresh ash deposits. It is usually difficult to obtain such large quantities of ash as: (1) there are no currently erupting volcanoes in New Zealand; (2) a number of eruptions occur in remote locations which are difficult to access quickly; and (3) New Zealand Ministry of Agriculture and Forestry bio-security regulations make it difficult to import such material into New Zealand. So to make this project practical and to control the physical and chemical properties of the ash used, a basaltic 'pseudo ash' was created. Mass production of a 'pseudo ash' in the Volcanic Ash Testing (VAT) Facility, University of Canterbury was developed by Broom (2010) and refined in this study. This chapter will outline the physical production of 'pseudo ash' and the development of a new dosing solution.

4.2. Physical Production

Basalt lava was chosen as the base material to create 'pseudo ash' as it is locally abundant and has similar chemical characteristics to volcanic ash. The Stoddart basalt used is from the Lyttelton Volcanic Group (Hampton, 2010) and was obtained from the Lyttelton Port of Christchurch owned Gollans Bay quarry in the Port Hills. The basalt is an olivine basalt lava which is holocrystalline, microporphyritic and has a trachytic texture (Guard, 1999). Olivine is the major microphenocryst phase with clinopyroxene, plagioclase, ilmenite dominating the groundmass. Blocks chosen were un-weathered (to avoid contamination from any alteration products), fine grained and 15-40 cm in diameter. In total, approximately 1 tonne of basalt blocks were brought back to the University of Canterbury, and stored outside the Department of Geological Sciences (Figure 4.1).

Figure 4.1: Stockpile of basalt lava blocks used to create 'pseudo ash'.

Prior to crushing, the basalt was cleaned with water and a wire brush to remove any organic material. Three different machines (Figure 4.2) were used to crush and mill the basalt, producing an ash-like texture. The basalt blocks were first split into 10 cm diameter pieces using a hydraulic rock splitter. These pieces were then fed into a jaw crusher which produced particles <5 mm in diameter. Finally a disk pulveriser was used, which milled particles to <1 mm in diameter. Particles >1 mm tended to be tabular in shape due to fracturing along crystal boundaries and did not resemble the morphology of volcanic ash. To reduce the concentration of these particles, the ash was passed through a 1 mm aperture sieve before being stored in two sealed 45 L copolymer polypropylene storage bins ready for dosing. In addition, ~15 L of 'pseudo ash' was passed through a 250 μm sieve to produce a fine grained 'pseudo ash'.

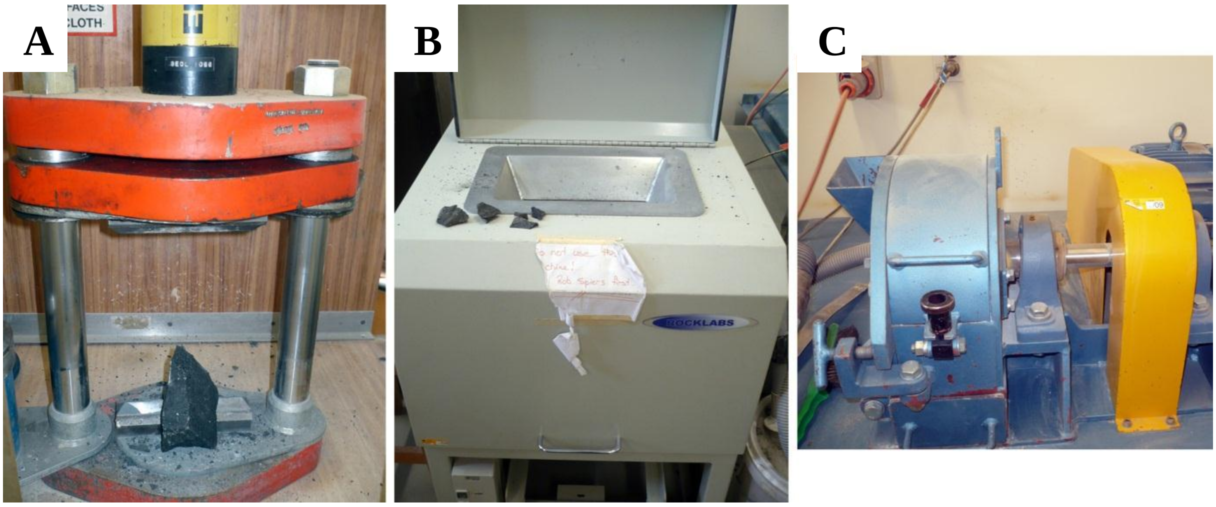

Figure 4.2: Machines used to create 'pseudo ash'. (A) hydraulic press; (B) jaw crusher; (C) disk pulveriser.

4.3. Physical Characterisation

To ensure that the correct grain size was achieved, the 'pseudo ash' was analysed with a Partica LA-950 laser diffraction particle size analyser at Massey University, Palmerston North and compared to five volcanic ash samples (Figure 4.3).

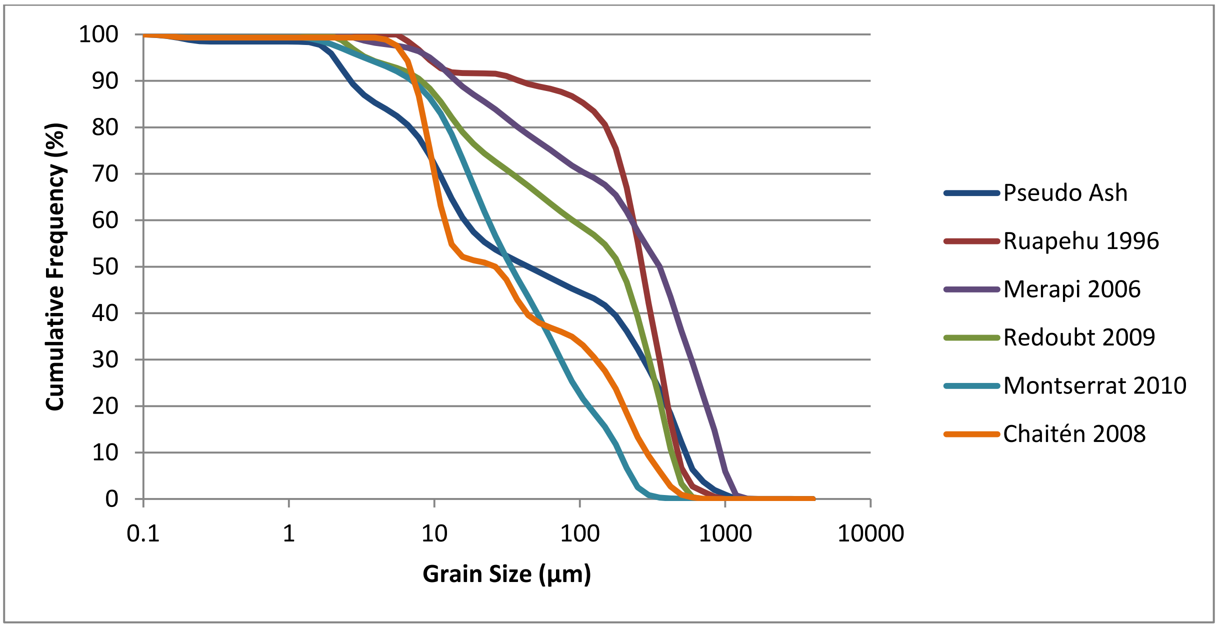

Figure 4.3: Grain size distribution comparison between 'pseudo ash' and five volcanic ashes.

The 'pseudo ash' sits within the range of Ruapehu, Merapi, Redoubt, Montserrat and Chaitén ashes, although it is nearer the fine end of this range, with ~25% of the sample less than 9 µm.

There are two significant peaks at ~176 µm and ~6.5 µm, which are similar to ones found in Redoubt ash (Figure 4.3) suggesting it may be due to how minerals (phenocrysts and groundmass) break up during magmatic fragmentation and mechanical crushing.

Other physical parameters such as density and particle morphology were not investigated for this thesis as Broom (2010) had previously undertaken these investigation for the same un-dosed 'pseudo ash'. He compared the density of 'pseudo ash' to five in situ ashes from the TVZ (Figure 4.4). The 'pseudo ash' had the second highest density at 1,572 kg/m^3, due to its fine grain size and basaltic composition, which is generally denser than other volcanic rocks. He did note that some of the in-situ samples contained large quantities of moisture which would cause an apparent increase in density. Density is an important parameter, as it controls the terminal velocity of falling particles, thus influencing ash deposits.

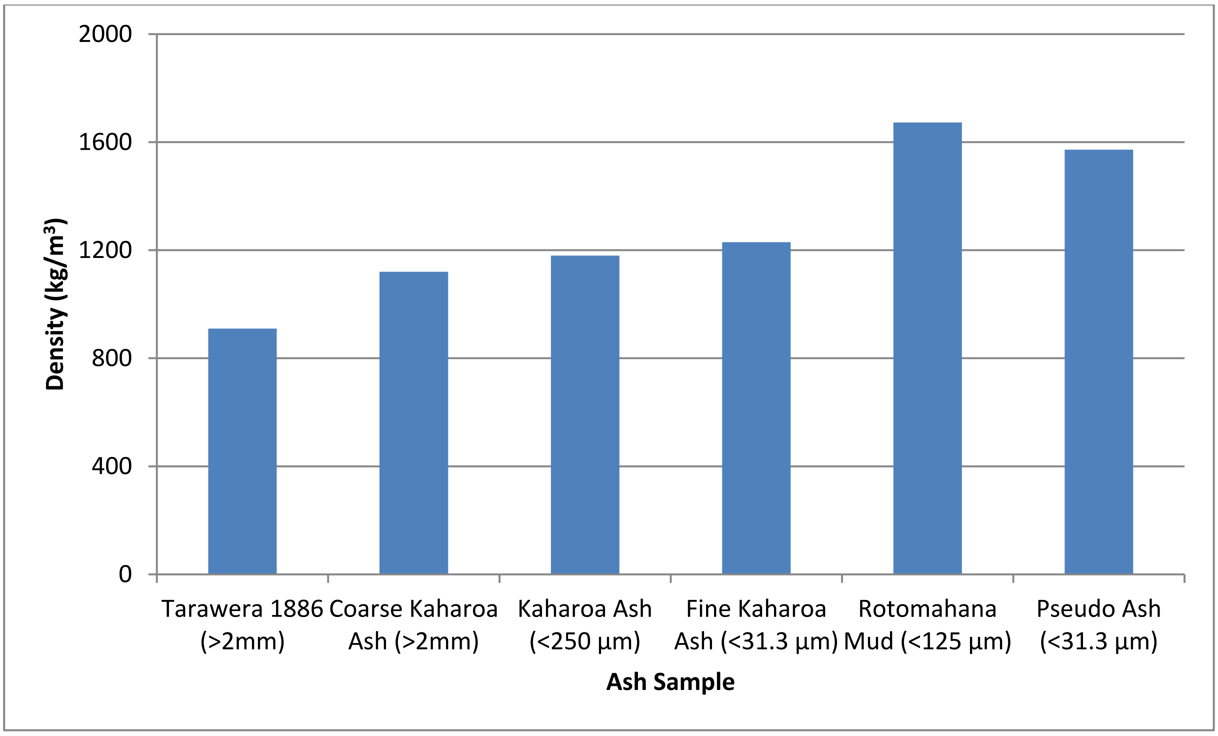

Figure 4.4: Comparison of in situ densities of five volcanic ashes and 'pseudo ash' (from Broom, 2010).

Broom (2010) also took images of the 'pseudo ash' with a scanning electron microscope (SEM) to compare particle morphology with that of volcanic ash samples (Figure 4.5). 'Pseudo ash' particles tended to be blocky in nature with angular edges, which often intersected at right angles. The main difference between volcanic ash particles and the ‘pseudo ash’ was that there was a lack of vesiculated surface morphology, typical of volcanic glass, in the ‘pseudo ash’ samples. This indicated that there was no volcanic glass within the ‘pseudo ash’. This may affect the abrasiveness of the ‘pseudo ash’ as angular glass shards tend to be the hardest of all the particles.

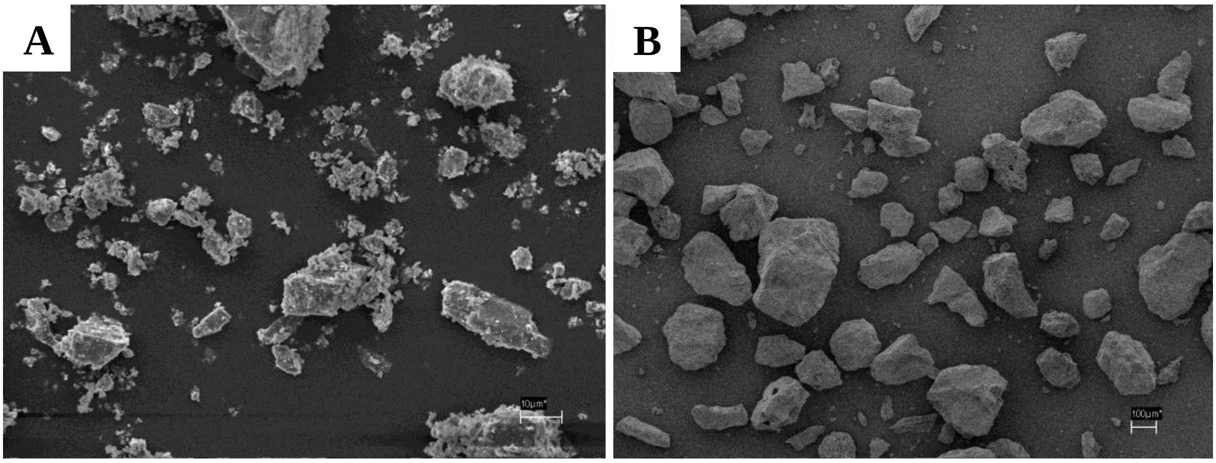

Figure 4.5: SEM image comparison of (A) ‘pseudo ash’ and (B) Ruapehu 1995-96 ash (from Broom, 2010).

4.4. Chemical Production

As volcanic ash is erupted, aerosols from the plume are scavenged by the ash particles, forming soluble salts (see Section 2.2.3.6). Therefore, any ash stimulant being created must take into account the presence of these soluble salts. The simplest and most practical way of doing this is to mix the raw ‘pseudo ash’ with a naturally occurring chemical solution. Once this has dried, various chemicals will have precipitated onto the ash surface. For this thesis the chemical solution used was water from Crater Lake, Mt Ruapehu, which was collected by GNS Science on 17 June 2010 as part of the GeoNet monitoring programme. A chemical analysis of the Crater Lake water is shown in Table 4.1.

Table 4.1: Chemical analysis of water from Crater Lake, Mt Ruapehu, collected by GNS Science on 17 June 2010.

Element	Concentration (mg/L)	Element	Concentration (mg/L)
Al	370	Li	0.77
B	17.2	Mg	1,067
Br	10.8	Na	660
Ca	909	NH_3	13
Cl	5,568	SiO_2	515
F	133	SO_4^{2-}	7,988
Fe	424	Sulfide	0.91
K	90	pH	1.13

4.4.1. Leachate Study

For the dosed 'pseudo ash' to be comparable to fresh ash the ratio of ash to chemical dosing solution and the concentration of the dosing solution needed to be calibrated. These parameters were calibrated by conducting leachate experiments. Three different ash to dosing solution ratios were used: 1:1; 2:1 and 4:1, with 100% concentration of the dosing solution used for all. A small quantity (30 g) of raw 'pseudo ash' was mixed with the appropriate amount of dosing solution and left to dry for two days at room temperature. Once dry, 1.25 g of dosed ash was added to 50 mL of distilled water (1:40 ratio) and placed in an end-over-end mixer for 24 hours. After mixing, samples were filtered using 0.2 µm syringe filters before being sent to the GNS Science Wairakei Analytical Laboratory for analysis. Ions analysed included: chloride, sulfate, fluoride, calcium, bromide, magnesium, as these are the most abundant species attached to ash particles (Witham *et al.*, 2005; Stewart *et al.*, 2006). Cations were analysed by inductively coupled plasma optical emission spectrometry (ICP-OES) and anions by ion chromatography (bromide, fluoride and sulfate), potentiometric method (chloride) and the methylene blue method (sulfide).

4.4.1.1. *Ash Leachate Results*

The ash leachate results are shown and compared to minimum, maximum and average leachate values of volcanic ash in Table 4.2.

Table 4.2: Concentrations of selected ions for three different dosed 'pseudo ashes' compared to minimum, maximum and average concentrations of ten volcanic ashes (Mount St. Helens Ash 1980, Fuego Ash 1973 and 1974, Pacaya Ash 1974, Santiaguito Ash 1967 and 1975, Ruapehu Ash 1995-96, Popocatepetl Ash 1994-96, 97, 98; see Table C.1, Appendix C).

Element	**'Pseudo Ash'**			**Volcanic Ash**		
	1:1, 100% (mg/L)	**2:1, 100%** (mg/L)	**4:1, 100%** (mg/L)	**Minimum** (mg/L)	**Average** (mg/L)	**Maximum** (mg/L)
Al	3.60	<0.15	<0.15	0.32	3.28	10.3
B	0.60	<0.30	<0.30	0.02	0.09	0.27
Br	0.15	<0.10	<0.10	0.30	0.30	0.30
Ca	29.0	7.30	7.20	29.6	104.9	211.6
Cl	79.0	21.0	21.0	4.07	49.9	205.9
F	2.0	0.41	0.41	0.64	3.24	7.20
Fe	3.20	<0.08	<0.08	0.10	0.60	1.56
Li	0.02	<0.01	<0.01	0.00	0.05	0.10
K	3.50	1.30	1.10	4.01	5.41	7.90
Mg	22.0	5.70	5.70	3.28	12.2	29.8
SiO_2	9.70	4.80	4.90	10.0	10.0	10.0
SO_4^{2-}	115.0	32.0	32.0	16.3	202.4	702.5

SO_4^{2-} is the most abundant species found in the 'pseudo ash' leachates and is due to large concentrations in Mt Ruapehu Crater Lake water (Table 4.1). The concentration is high in this water because SO_4^{2-} is the stable end product of a number of dissolution and oxidation reactions that take place in the lake (Christenson and Wood, 1993). When compared to leachate values from real volcanic ash, all dosing strengths are above minimum values but well below average values. The next most abundant species in the 'pseudo ash' leachates are Cl, Ca and Mg respectively. Cl and Mg concentrations for the 2:1 and 4:1 strength 'pseudo ash' are above minimum concentrations when compared to real volcanic ash leachates, whereas the 1:1 strength is above average values. Cl and Mg concentrations are high because

Mt Ruapehu Crater Lake water is enriched in these elements (Table 4.1), as Cl derived from fumarolic steam, mainly as HCl, from fumaroles on the crater floor, and Mg is derived from the interaction of hot acidic water with fresh magmatic material (Giggenbach and Glover, 1975). Ca concentrations are below minimum values in all ‘pseudo ash’ strengths.

Comparing the ratios of Ca and Mg for ‘pseudo ash’ and Mt Ruapehu Crater Lake water, shows that Ca was more efficient at being deposited onto the ash than Mg. This is possibly due to the acidic dosing solution attacking plagioclase and pyroxene minerals in the basalt releasing more Ca. Both B and Fe showed concentrations higher than the maximum concentrations for volcanic ash leachates. However this was only for the 1:1 sample, as the other two samples had concentrations below the detections limits of 0.30 and 0.08 mg/L, respectively (Table 4.2). It is unknown what has caused these increases in only one sample.

F appears in relatively low concentrations, with the 1:1 sample having concentrations higher than the minimum, but lower than the average, ash leachate concentrations, while the 2:1 and the 4:1 sample have lower concentrations. This is however an important ion as it is the principal toxic element absorbed onto ash particles (Witham *et al.*, 2005).

Overall the 1:1 dosing strength is the best approximation to volcanic ash leachates; however, to dose the ash at a 1:1 ratio requires large quantities of Mt Ruapehu Crater Lake water which cannot be obtained easily. Therefore, for this thesis the 2:1 dosing strength was used. This still has a good approximation to volcanic ash leachates for the majority of the ions measured, and also requires less Mt Ruapehu Crater Lake water.

4.4.2. Mass Dosing

As large quantities of ‘pseudo ash’ were required for vulnerability testing, large quantities had to be dosed. Six kilograms of raw ‘pseudo ash’ was weighed out into a 12 L polypropylene container and was thoroughly mixed with 1.9 L of dosing solution (2:1 ratio by volume). The slurry was dried in an oven at 80 °C for four days to speed drying, as Broom (2010) found no difference in chemical composition of dosed ‘pseudo ash’ when dried at room temperature or in an oven.

After four days of drying, the mixture formed cemented aggregations that needed to be broken up into individual grains. This was done using the disk pulveriser which was set to a coarser setting than when originally producing the ash, in order to only break up the cemented aggregates and not affect the original grain size distribution. The dosed ash was kept in sealed 45 L copolymer polypropylene storage bins until required.

Chapter Five – Analysis of Volcanic Ash Impacts to Laptop Computers

5.1. Introduction

As mentioned in Chapter One, laptop computers are becoming increasing popular in all areas of society and as a result their risk to volcanic hazards is also increasing. In order to reduce this risk, the vulnerability of laptop computers and components needs to be determined. This can be achieved through experimentation in the field of volcano engineering. The results of these experiments will then help inform the development of appropriate risk mitigation techniques. This chapter outlines the ash vulnerability experimentation and mitigation technique development undertaken as part of the risk analysis stage in this thesis.

5.2. Testing Methodology

5.2.1. Test Set Up

A test chamber was built in the VAT Facility in the Geological Sciences basement at University of Canterbury. It consisted of a large Perspex box (1.2 x 1.0 x 0.8 m), plastic sheeting and ash delivery system (Figure 5.1). A metal frame was constructed around the testing chamber to secure it to the wall and to hold the ash delivery system above the chamber. To increase air circulation inside the testing chamber, and to help circulate ash evenly around the chamber, two 120 mm diameter computer cooling fans were placed in the chamber base and two 230 mm diameter desk fans were located inside the chamber (Figure 5.2).

Figure 5.1: Front view of testing chamber showing ash delivery system, plastic sheeting and Perspex box within the VAT Facility.

A laptop stand constructed out of wood and steel was placed at the bottom of the box in the centre (Figure 5.2). This lifted the laptops off the base of the Perspex box by 100 mm allowing the computer cooling fans room to circulate the ash. To monitor the temperature and relative humidity inside the chamber during the experiments, as these parameters play a role in corrosion (see Sections 2.2.3.6 and 2.3.2), a temperature and humidity logger (Lascar EL-USB-2+) was mounted near the top of the box, out of the ashfall zone.

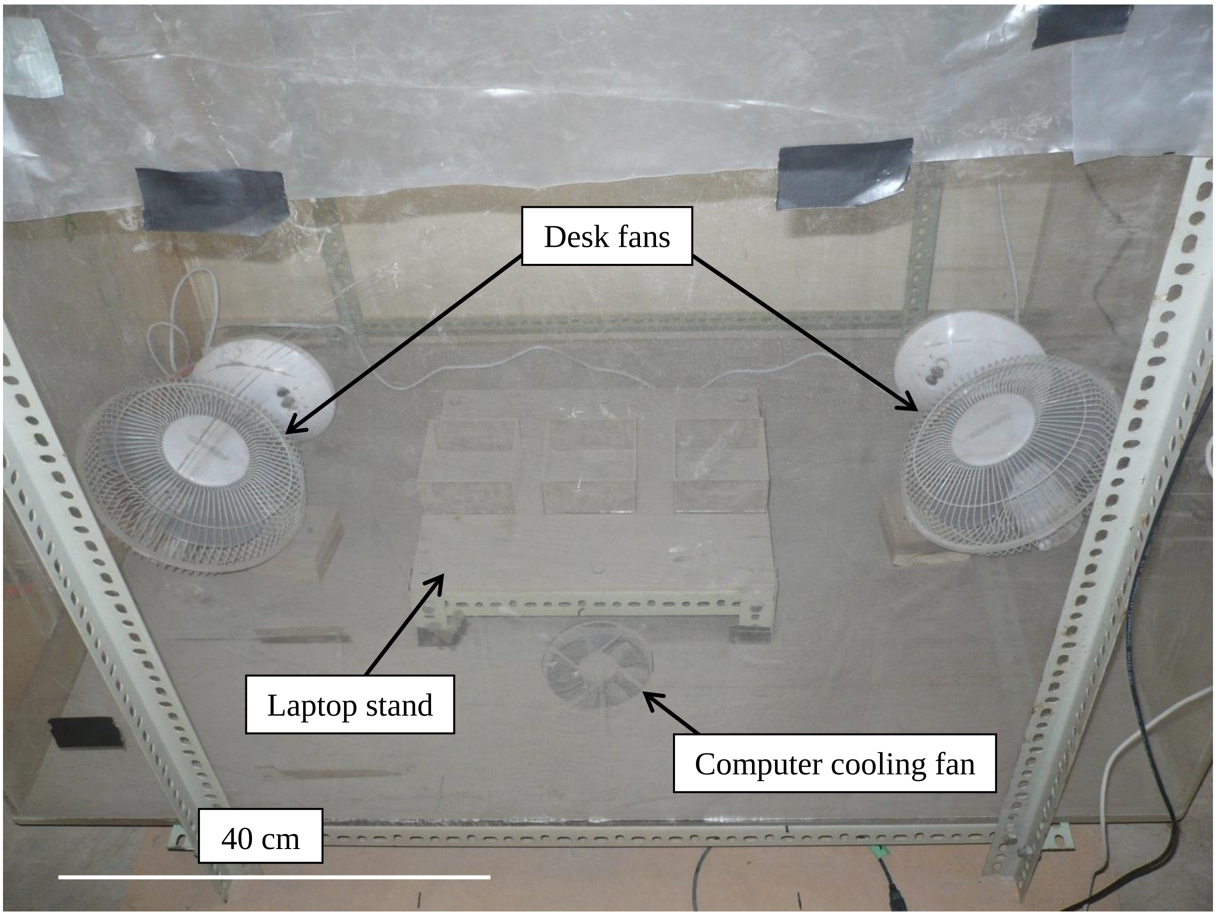

Figure 5.2: Front view of testing chamber showing two desk fans (left and right); the laptop stand (centre); and one of the computer cooling fans (centre) in test configuration.

An automated ash delivery system was constructed to deliver ash into the test chamber consistently over a long period of time at a known rate. A number of different designs were considered, and it was decided that sieving the ash would be the most appropriate method, as this would spread the ash over a wide area and give an even distribution at a controlled rate. A 400 x 400 x 100 mm sieve box was constructed which had a stainless steel mesh (~1 mm aperture) base. This was mounted on a wood and steel frame above the Perspex test chamber. In order to automate the ash delivery, the sieve was mounted on draw runners and connected to a 12V 160 RPM DC motor via a cam and shaft. This provided the sieve with a 50 mm side-to-side motion. The motion achieved was far from satisfactory and led to inconsistent ashfall and an uneven ash distribution on the base of the test chamber. Eventually the motor burnt out from the stress of the 'rough' motion. A second design was developed where the side-to-side motion was replaced by a striking motion. With this design, a cam attached to a new motor moved to release a spring loaded hammer, which struck the edge of the sieve, providing a small vibration, causing ash to fall though. To keep the sieve in place it was connected to the metal frame with screws and rubber stoppers. After some preliminary calibration testing, which produced an uneven ash distribution, two small strips of metal were attached to the underside of the sieve to transfer the vibration of the hammer strike throughout the sieve, thus providing an even ash distribution. The motor used in this system was wired to a controller allowing variable speed control of the motor and changes in the ashfall rate.

5.2.1.1. Ashfall Parameters

In order to make the simulated ashfall realistic, the height the ash falls from and the ash accumulation rate had to be considered in the ash delivery system design. Wilson and Huang (1979) suggest that a height of ~0.3 m is sufficient for ash particles, with mean diameters of 800 µm, to reach terminal velocity. Working within the height restrictions of the laboratory space and taking into account ash particles up to 1 mm in diameter, a height of 1.27 m was chosen, allowing most particles in the ‘pseudo ash’ grain size distribution, sufficient time to reach terminal velocity.

Ashfall accumulation rates are dependent on the style of eruption and the conditions at the time of the eruption. Rates up to ~6,000 g/m^2 h (Brazier *et al.*, 1982) have been documented in previous studies. For these experiments, a rate of ~500 g/m^2 h was chosen, which allowed an ash rich environment to exist in the testing chamber, but prevented ash rapidly covering the laptop and restricting it from drawing in ash laden air.

To calibrate the ash delivery system to this accumulation rate, a number of small experiments were undertaken. These consisted of turning on the ash delivery system for a set amount of time, between 1-5 hours, while three small Perspex boxes (100 x 100 x 50 mm) on the bottom of the testing chamber collected the ash. The accumulation rate was calculated by using the surface area of the small Perspex boxes (0.01 m^2) and the mass of ash they collected. The rates ranged from ~110 to ~2,800 g/m^2 h depending on the speed of the ash delivery system motor and the position of the collection boxes in the testing chamber. The easiest rate to achieve during the calibration experiments was ~1000 g/m^2 h as the motor had consistency problems going slow and fast. Therefore, to achieve the desired ashfall accumulation rate of ~500 g/m^2 h, the ash delivery system was connected to an electronic timer which repeated a

15 minute on, 15 minute off cycle, i.e. the ash delivery system was on for 30 minutes every hour the experiment was running, thereby halving the accumulation rate of the delivery system. This also simulates a pulsing volcanic eruption.

5.2.2. Computer Setup

The laptops used for these experiments ranged from 5-10 years old, and were in good working order. They were donated by various individuals and companies and were a range of different makes and models. The specifications of each laptop are listed in Appendix D and the basic operation of a laptop is explained in Appendix E. The laptops had either Microsoft® Windows® 2000 or Microsoft® Windows® XP operating systems installed depending on the laptops specifications. PassMark® BurnInTest™ V6.0 Pro, SpeedFan and System Monitor software were also installed for conducting the computer testing and monitoring. These three pieces of software were setup to run as soon as the computer turned on.

PassMark® BurnInTest™ V6.0 Pro was chosen because it "…is a software tool that allows all the major sub-systems of a computer to be simultaneously stress tested for endurance, reliability and stability" (PassMark website, 2010). The software allows for cyclic testing of the central processing unit (CPU), random-access memory (RAM), hard drives, compact disk (CD) drives and graphics chips, while logging any errors. The software does not damage the components but makes them operate under full load. Testing for 24-72 hours is equivalent to using the computer under low loads for several consecutive weeks (Gordon *et al.*, 2005). The tests used for these experiments are as follows:

- CPU test: In this test, the CPU carries out difficult mathematical calculations millions of times. The test cycles through four different types of calculations every half a second.
- RAM test: This test writes and reads a pattern of numbers from the available RAM. The pattern is changed after each write/read cycle.
- 2D graphics test: This test writes a pattern of numbers to the video memory, which is then displayed on the screen. Once displayed, the test pattern is read from the video memory and verified.

- 3D graphics test: This test creates an animated 3D image to test the 3D performance of the graphics card. The animation consists of a plane flying around over terrain, tress and water. Some of the older laptop computers could not undertake this test due to their limited hardware.
- Hard drive test: This test writes then reads a number pattern file to and from the primary hard drive. The size of the file is 1% of the hard drive capacity, so varies for each laptop. The pattern of numbers is randomised each write/read cycle.
- CD drive test: This test reads and verifies ~20,000 files from a PassMark® data CD.

The load of each test can be set between 0% (no load) and 100% (full load) within the BurnInTest™ software. Loads for these experiments were set between 50-80% depending on the laptops specifications (Table 5.1).

Table 5.1: BurnInTest™ test loads for laptops used in ash vulnerability testing.

Laptop	Test Loads					
	CPU	RAM	2D Graphics	3D Graphics	Hard Drive	CD Drive
1	50%	50%	50%	50%	50%	50%
3	80%	80%	80%	80%	80%	80%
5	80%	80%	80%	80%	80%	80%
7	80%	80%	80%	80%	80%	80%
9	80%	80%	80%	80%	80%	80%
10	80%	80%	80%	80%	80%	80%
11	60%	60%	60%	60%	60%	60%
12	60%	60%	60%	60%	60%	60%
17	50%	50%	50%	50%	50%	50%
18	50%	50%	50%	50%	50%	50%

To display and log the temperatures of various sensors inside the laptops, a software tool called SpeedFan was used. This software was used to indicate if certain components overheated during the experiment. The number of temperatures recorded for each laptop depended on if the hardware was supported by SpeedFan.

To monitor the laptop's CPU and RAM loads during the experiments, a piece of software called System Monitor was used. This software records the loads in a log file which can be displayed graphically.

To overcome the possibility that the laptops hard drives could fail during the test, the software and associated log files were run and saved to a universal serial bus (USB) flash drive which was located outside of the testing chamber. The laptops were connected to a screen and mouse, which were also located outside the testing chamber. These items made the laptop easy to operate, if need be, while covered in ash.

Prior to the ash vulnerability experiments, each laptop was dismantled and photographs of key components (hard drive, CD drive, motherboard, RAM, etc.) were taken. These photographs were then compared to photographs taken after ash exposure.

5.2.3. Testing Procedure

5.2.3.1. Laptop Computer Testing

At the start of each experiment the laptop was placed on the laptop stand in the centre of the testing chamber and connected to the external USB flash drive, screen, mouse and power. The fans inside the testing chamber were also started at this time. The laptop and stress tests were started and run for 24 hours without the introduction of ash, to determine if the laptop was running correctly and to allow the chamber's temperature and humidity to stabilise.

After the pre-test, 10 kg of dosed 'pseudo ash' was loaded into the ash delivery hopper above the testing chamber. The ash was loaded carefully from a dustpan in order to minimise the amount of ash that fell through the sieve. The experiment commenced when the ash delivery system was turned on. The experiment was run continuously for up to 5-7 days, unless laptop failure occurred prior, as this was the time at which desktop computers failed in the Gordon *et al.* (2005) study. During the experiments, photographs of the laptop were taken every hour by a webcam mounted outside the testing chamber, to provide visual information about ash accumulation. Additionally, photographs were taken of all sides of the laptop each day, as well as detailed notes about ash accumulation and distribution and computer performance.

At the end of the experiment, the ash delivery system and cooling fans were turned off, and the laptop shutdown. The laptop was unplugged from the power, screen and USB cables and carefully removed from the testing chamber and placed on a rack for examination (Figure 5.3). Prior to ash removal and laptop dismantling, photographs were taken of the outside of the laptop. In order to examine the inside of the laptop, ash was carefully removed from the keyboard and surrounds with a small paint brush and dustpan. This allowed the laptop to be dismantled without the introduction of stray ash onto the laptop's components. Photographs were taken of each component in order to compare them to pre-exposure photographs. Detailed notes of the location of any ash, quantity and approximate grain size were also taken. The data produced by the software running on the laptop was downloaded for analysis.

Figure 5.3: Rack used to examine laptops after ash vulnerability testing. This rack allows the laptop to be examined and dismantled without being turned over, thereby preserving the ash coverage.

5.2.3.2. Humidity Testing

To undertake ash vulnerability experiments with moist ash, a humidifier was used to increase the relative humidity in the testing chamber to ~95%. This method allowed the ash to absorb moisture as it fell, preventing the ash particles clumping together as would be the case if the ash was wet prior to being loaded into the ash delivery system. Also it proved difficult to sieve wet ash.

The same testing procedure as described in Section 5.2.3.1 was used for these experiments. The only changed was that the humidifier was turned on 24 hours prior to the introduction of ash to allow the testing chamber's temperature and humidity to stabilise.

5.2.3.3. Keyboard Testing

Laptop keyboards were tested because they are one of two user input devices on a laptop, the other being the mouse pad, and if they cannot be used, laptop functionality decreases. In addition, keyboards are very likely to be directly impacted by ash, as they take up the majority of the area on the top side of a laptop. In order to provide a comparison, desktop keyboards were also tested. Both laptop and desktop keyboards were exposed to a range of accumulation thicknesses and grain sizes of 'pseudo ash' to determine their performance in an ash environment. Four grain sizes (<125, 125-250, 250-500 and 500-1,000 µm) were used at a thickness of 2 mm, and one grain size (250-500 µm) was used at four thicknesses (3, 5, 10 and 20 mm). Prior to exposure, one keytop from each keyboard was removed so photographs of the key switches could be obtained for comparison to photographs taken after exposure. The functionality of each keyboard was checked using PassMark® KeyboardTest™ software. This software indicates which keys are currently working and which are not, by showing graphical information on the screen. Each key was tested five times.

The keyboards, and in the case of the laptop keyboards, the laptop as well, were placed inside the testing chamber one at a time. 'Pseudo ash' was then shaken over the keyboard from a 1 mm aperture sieve at a height of 1.27 m above the keyboard, providing an even distribution of ash over the entire keyboard. Once the desired thickness of ash was reached, the keyboard was removed for examination. Examination involved taking photographs and removing the same key as before ash exposure to examine the switch. Functionality of the keyboards was again checked using PassMark® KeyboardTest™ software.

Once the relevant information had been obtained, each keyboard was cleaned by tipping it upside down and cleaning it with compressed air and a soft brush.

5.2.3.4. Hard Drive Testing

Hard drives were tested individually under direct ashfall to determine their vulnerability, as they are the primary means of laptop data storage. If hard drives fail, the laptop will no longer work and any data will be lost. The hard drives were connected to a laptop via a USB cable and put under the same hard drive stress test as used for the laptop testing (Section 5.2.2). Once the BurnInTest™ software had completed one test cycle, ash was introduced at the same rate as for the laptop testing.

5.3. Results

5.3.1. Laptop Computers

After testing ten laptop computers for 100-160 hours with dry and wet ash and fall thicknesses up to ~100 mm, none permanently failed. However, three laptops did shutdown temporarily due to overheating. Additionally, some components had a reduction in functionality.

During testing, ash accumulated in large quantities, up to ~100 mm thick, on top of keyboards, preventing them from being used until the ash was removed. Section 5.3.2 contains results of more detailed keyboard testing. One laptop was tested with its lid closed and although the same amount of ash accumulated inside this laptop, compared to the lid open laptops, the keyboard was only covered with trace quantities of fine ash.

As ash fell, it accumulated in 'mini-fans' between keyboards and screens (Figure 5.4). This ash blocked the lower portion of screens and limited their movement, as ash became stuck in the hinges. Ash also accumulated in 'mini-fans' between the sides of the laptops and the ground (Figure 5.5). These ‘mini-fans’ caused any external ports (USB, screen, parallel, network, etc.) that were not in use at the time to become blocked with ash and unusable until thoroughly cleaned with compressed air. As these ‘mini-fans’ increased in height, ash that was <500 μm in diameter, was able to fall inside the laptops through holes in the case, such as the expansion card slot and any air intake holes. Ash also blocked cooling fan outlets, limiting airflow through the laptop causing some to operate at temperatures ~5-10 °C higher than temperatures prior to ash introduction (Appendix F). It was also noted that during a rapid period of ashfall for one laptop test (laptop 3), the internal temperature of the laptop increased ~20 °C over ~8 hours and remained at elevated temperatures for the remainder of the test (Figure F.10). It is likely that this increase in temperature was related to the thickness of ash on the laptop and its potential insulating effect.

Figure 5.4: Ash forming a ‘mini-fan’ between the laptop’s screen and keyboard.

Figure 5.5: Ash forming a 'mini-fan' around the sides of the laptop, blocking ventilation holes.

After testing, each laptop was systematically pulled apart and examined. Each laptop had up to ~1 cm^3 of fine grained ash (<250 μm), irrespective of ash grain size used for testing, distributed over the motherboard, microchips and other internal components (Figure 5.6). In some cases, microchips were completely covered in ash, however they still operated flawlessly. Larger quantities (~2 cm^3) of coarse ash (500-1,000 μm in diameter) were located around large openings in some laptop cases, such as the expansion card slot and air intake and exhaust holes. Trace amounts of fine ash were found under RAM, battery and hard drive covers on the bottom of some laptops. However this ash generally did not make it onto the components and remained attached to the plastic covers.

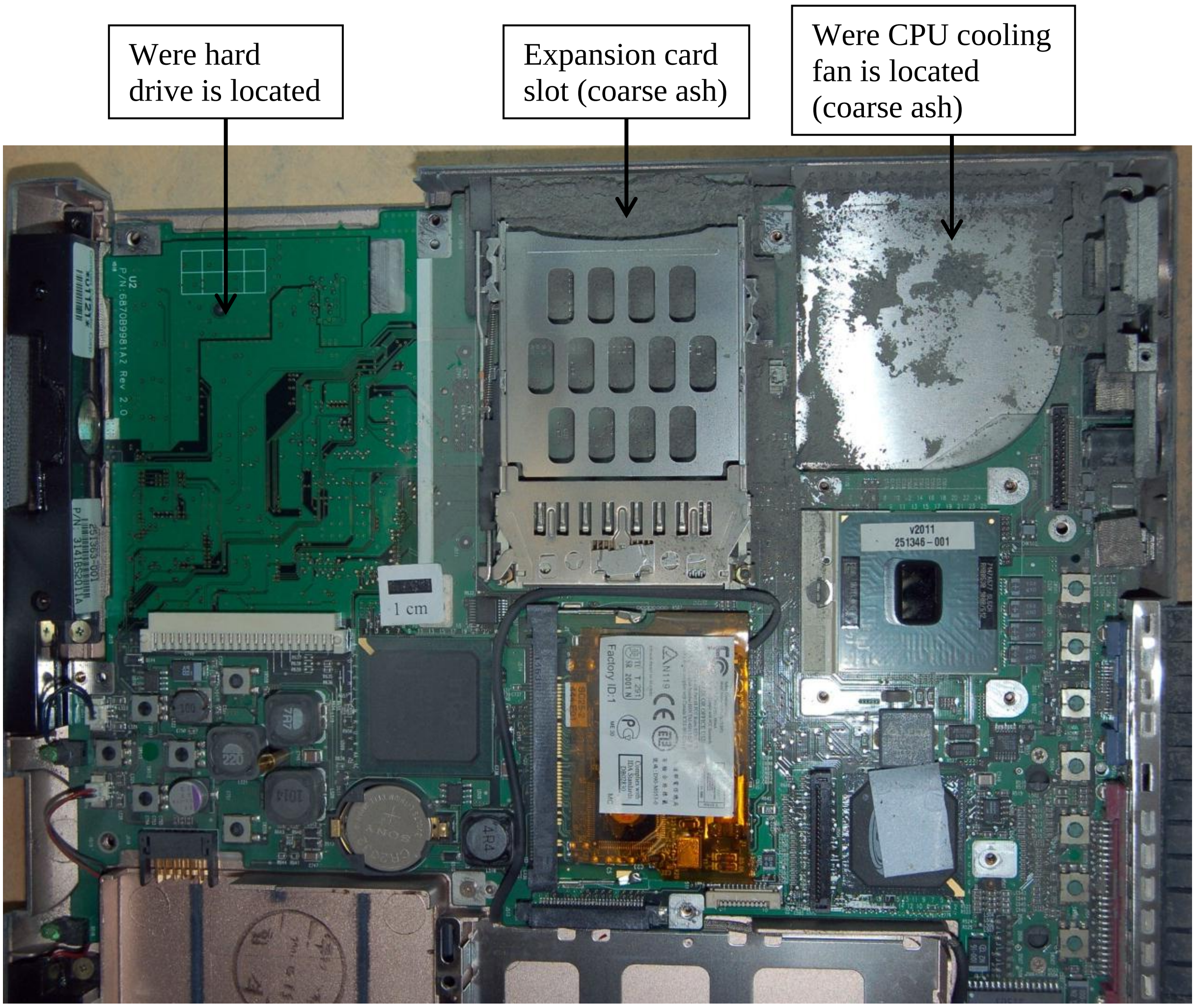

Figure 5.6: Laptop motherboard covered in a thin layer of fine grained volcanic ash (light grey colour) after 120 hours of testing. Coarse ash particles are located around the cooling fan opening (top right) and expansion card slot (top middle). Hard drive is normally located in top left, but has been removed for this photograph, which has resulted in the motherboard underneath being void of ash.

All but one of the laptops tested had a CPU cooling fan and Cu heat sink to provide cooling for the CPU. The heat sink transfers heat from the CPU to the surrounding air through a series of narrow Cu fins. The cooling fan then takes air from outside the laptop and forces it through the fins, thus removing hot air from the laptop. After exposure to ash, it was found that fine grained ash had coated fan blades of all the cooling fans (Figure 5.7). Fine grained ash (<250 μm), and in some cases coarse ash (>500 μm), had collected in the fan housings and within the fins of the heat sinks, causing partial blockage of the heat sink fins, thereby reducing their efficiency.

Figure 5.7: Fan blades of a cooling fan covered with a thin coating of fine grained volcanic ash after 140 hours of testing.

In addition, trace quantities of fine ash were found inside the fan motor on one cooling fan after a fine grained (<250 μm) ash test. The motors used in cooling fans are a brushless DC type, which use electromagnets coils and a permanent magnet to spin the fan blades. Figure 5.8 shows the typical configuration of cooling fan motors.

Ash was found between the permanent magnet and the electromagnets coil supports, which are spaced ~1-2 mm apart. Once the ash was removed, a few small scratches were found on the permanent magnet, indicating that the ash had abraded the magnet's surface, however, it was still able to operate normally. In another laptop, <0.25 cm^3 of ash had accumulated inside the fan motor, causing it to become jammed. It is unknown when this fan jammed, however the laptop did restart ~70 hours into the test. This restart was likely caused by excess heat build-up as a result of the jammed fan, as the internal temperature of the laptop was constant at 49 °C prior to the restart and increase to 90 °C after the restart (Figure F.14). Nevertheless, the laptop continued to operate at 90 °C with no further problems until the completion of the test, ~32 hours later. Once the ash was cleaned out of this fan, it worked normally. No ash was found near or inside the any of the fan bearing assemblies as they are well sealed and protected inside the fan casing.

Figure 5.8: Desktop fan showing the configuration of the components within the motor. The plastic cover that covers these components has been removed for this photograph.

Trace quantities of fine ash were found inside the CD drive and on the test CD in all of the laptops (Figure 5.9). Ash was generally found around the CD drive openings towards the outside of the laptop and on the top side of the CD. However, ash was occasionally found on the lens, which covers the laser, and on the bottom side of the CD. Half of the CDs used were scratched to various degrees during testing by either ash particles or by making contact with components within the CD drive. The covering of ash on the CDs and lens and the scratches meant that it was difficult for the laser to read the CD, leading to a reduction in functionality. This was indicated by numerous read errors logged by the BurnInTest™ software (Table 5.2).

Table 5.2: Total number of CD drive errors reported by the BurnInTest™ software during ash vulnerability tests for each laptop.

Laptop	CD Drive Errors	Laptop	CD Drive Errors
1	1,501	11	7,923
3	810	12	0
4	0	17	2,078
9	0	18	2,857
10	0		

During laptop testing, no hard drives failed as they are relatively well protected inside laptops. Additional testing of hard drives was undertaken, where the hard drive was removed from the laptop and placed directly in the testing chamber. Again with this testing, no hard drives failed after 24 hours of ashfall. However, after the vacuum seals and air filters were removed, failure occurred after only ~2 minutes of ashfall. A few small grains were found inside the hard drive, but most importantly they were under the read/write head. This meant the head could no longer read the data from the disk. This result is comparable to what Gordon *et al.* (2005) found with desktop hard drives.

The function of the mouse pads and buttons was also tested during exposure. The buttons did not fail at any ash thickness or grain size. However, the mouse pad reduced in functionality by ~50% at thicknesses >2 mm and grain sizes >125 μm.

Upon examination of laptops that had been exposed to a high humidity (~95%) ash environment, it was found that there was no ash covering the motherboard or other internal components. However, trace quantities of fine ash were found inside the case near ventilation holes. During these tests, moist ash had adhered to the external connectors and to some parts of the plastic case. These areas proved difficult to clean.

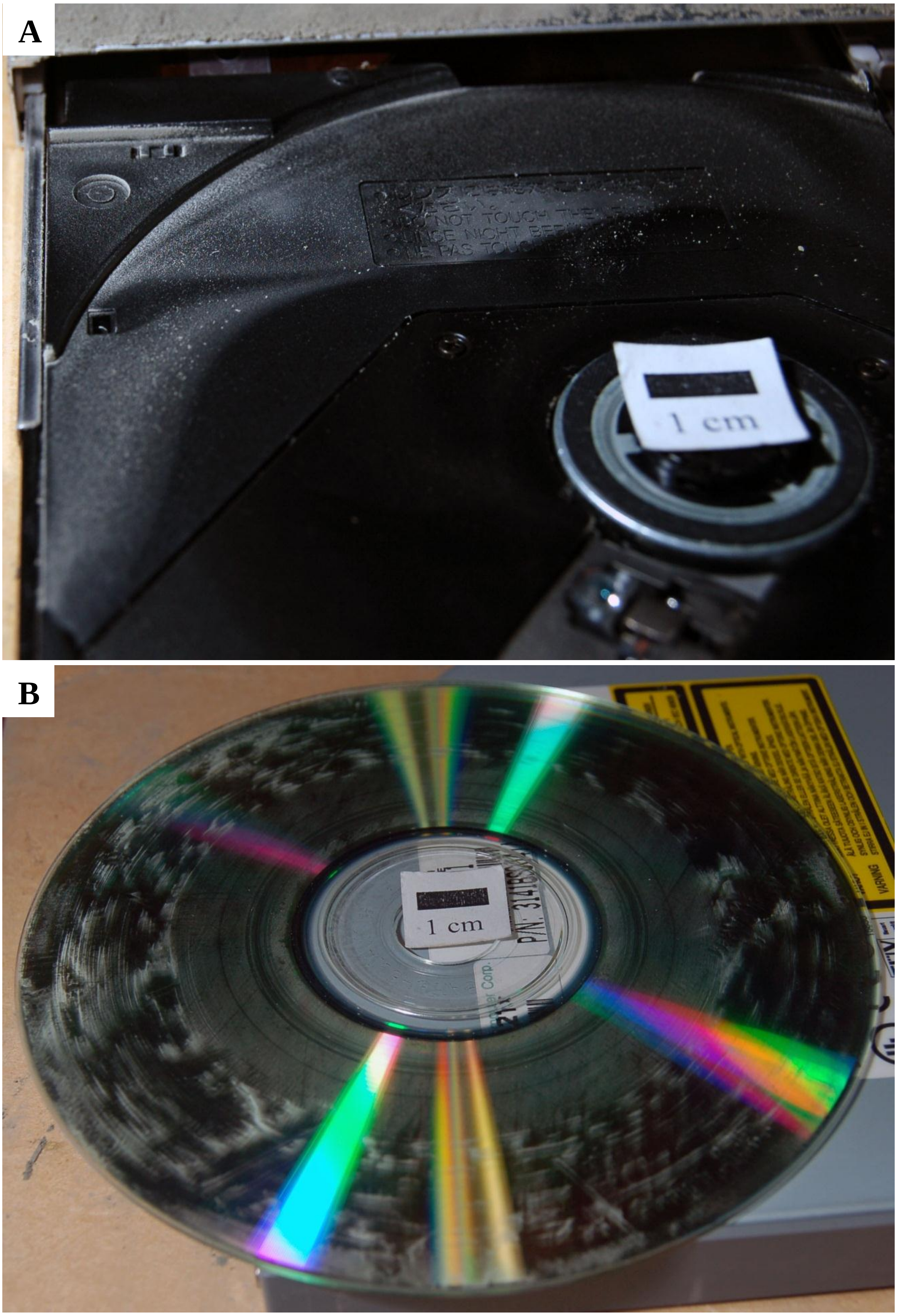

Figure 5.9: (A) CD drive tray with a small quantity of fine grained volcanic ash (light grey) in one corner. (B) Bottom side of a CD covered with fine grained volcanic ash and some scratches.

5.3.1.1. Laptop Computer Cleaning

Once the examination of each laptop was complete, they were cleaned with a soft bristled brush and compressed air. Cleaning the inside of the laptops, to a reasonable standard, was relatively easy and took <10 minutes, although, cleaning time did increase as the ash grain size decreased. On a few occasions the entire laptop had to be completely pulled apart to remove all traces of fine grained ash. Cleaning the outside of the laptops case proved more difficult, as the ash adhered to the plastic case more so than the motherboard. With moist ash, vigorous brushing was required to remove all traces of ash from the outside of the case. After cleaning laptop screens with a brush and compressed air, trace amounts of ash still remained and was only able to be removed with a damp cloth. CDs also had to be cleaned with a damp cloth in order to remove all traces of ash.

5.3.2. Keyboards

Overall desktop keyboards performed better than laptop keyboards for all ash grain sizes and thicknesses tested. Key functionality tests showed that as grain size decreases key functionality increases for both types of keyboards (Figure 5.10) and as ash thickness increases key functionality decreases for both types of keyboards (Figure 5.11).

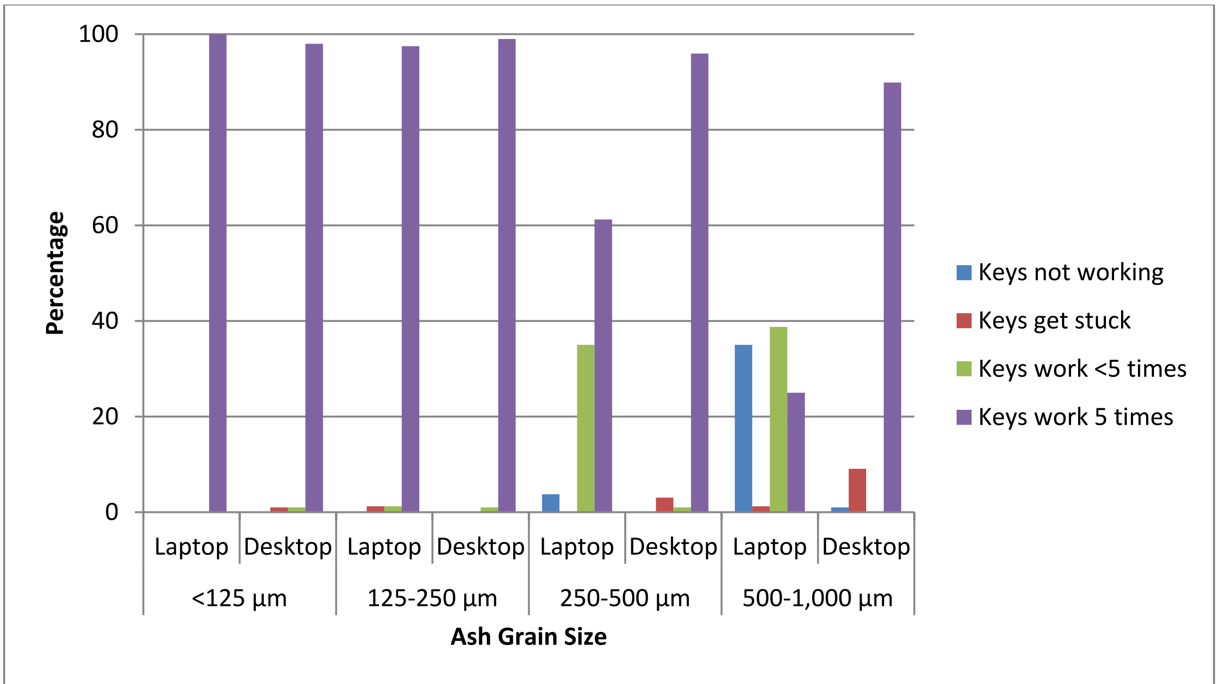

Figure 5.10: Key functionality of laptop and desktop keyboards with different ash grain sizes.

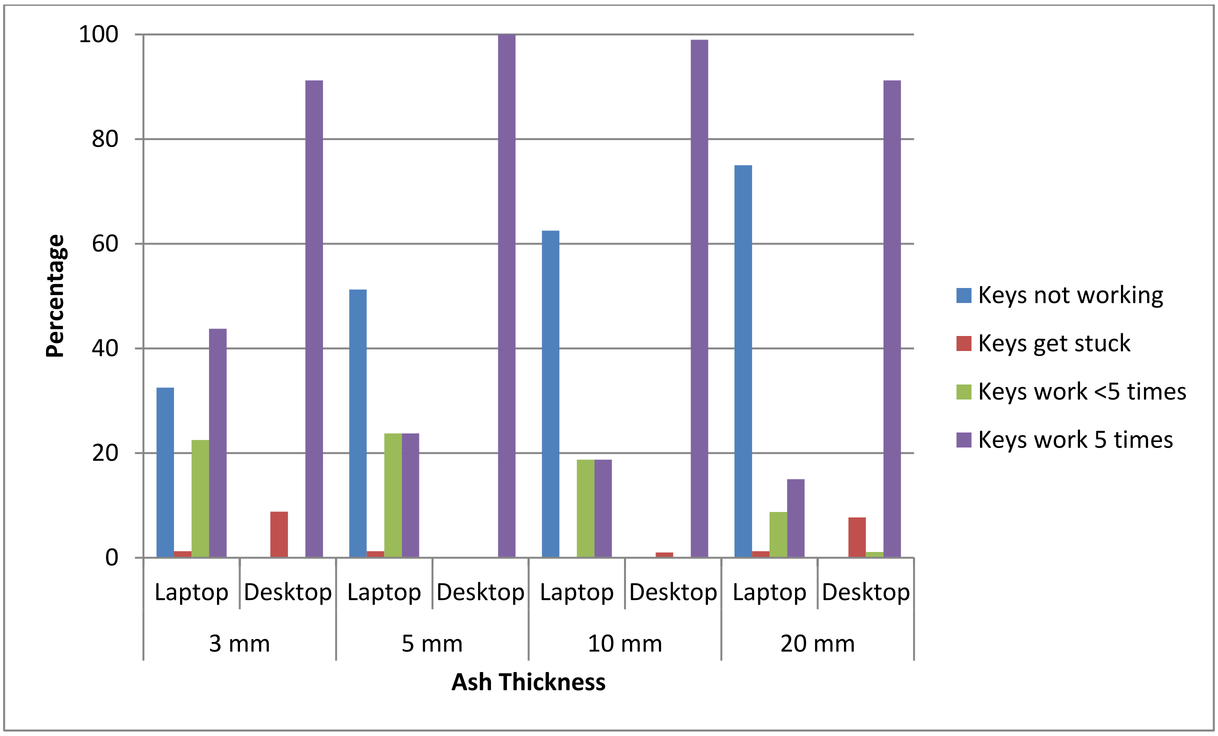

Figure 5.11: Key functionality of laptop and desktop keyboards with different ash thicknesses.

Surprisingly >90% of keys on desktop keyboards functioned correctly for all ash grain sizes and thicknesses, including a covering of 20 mm of ash. In comparison, laptop keyboards performed poorly for grain sizes >250 µm, with only up to 60% of keys functioning after ash exposure and 40% of keys either not working or only working sometimes. At grain sizes <250 µm, laptop keyboard performance improved, with ~98% of the keys functioning correctly. As ash thickness increased from 3 to 20 mm, the percentage of laptop keys not functioning increased from 30% to 75%, although 15% of the keys still functioned correctly with a 20 mm covering of ash. After ash exposure, slightly more keys became stuck on desktop keyboards than on laptop keyboards, although the percentage of keys becoming stuck was <10%.

Upon removal of a key for examination, it was found that both types of keyboards had collected similar quantities (<0.5 cm^3) of ash under the key in each of their respective tests (Figure 5.12). However no ash had collected around the key switch or on the electrical membrane in the base of the keyboard.

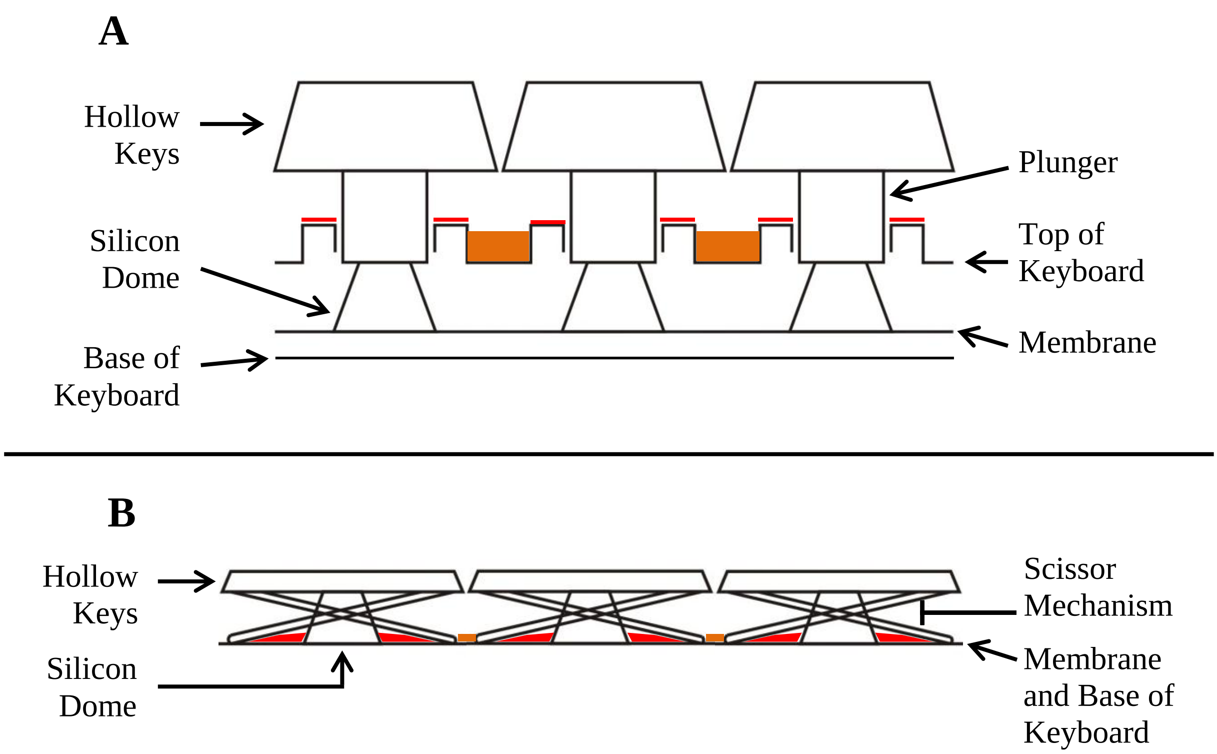

Figure 5.12: Cross section of keyboard keys for (A) desktop keyboard and (B) laptop keyboard. Orange represents large ash accumulation, red represents trace ash accumulation. A key press is registered when the top of the silicon dome makes contact with the membrane.

After each test, each keyboard was cleaned by first tipping the keyboard upside down, then by tipping in on its side and gently tapping the other side to allow the ash to fall out. This was followed by quickly spraying the keyboards with compressed air. Desktop keyboards took longer to clean than laptop keyboards and in some cases each key had to be removed in order to remove all of the ash and return the keyboard to 100% functionality. It was noted that the cleaning time increased, for both keyboard types, from ~5 minutes to ~15 minutes as ash grain size decreased.

5.4. Discussion

5.4.1. Laptop Computers

The results show that small quantities of ash did get inside laptop computers, through holes in the case, cooling fans and keyboards. However, this caused little damage, suggesting that laptop computers, overall, have a relatively low vulnerability to volcanic ash. This is due to the internal layout and component design of laptops compared to desktop computers, as well as the particular layout of each laptop. Nevertheless, two components (CD drive and cooling fan) were vulnerable to volcanic ash.

5.4.1.1. Ash Ingress and Distribution inside Laptop Computers

The reason there was so little ash inside laptops was because of their compact design. This design leaves little room for large cooling fans, air intake and exhaust holes, which would allow more ash into the laptop. Cooling fans on laptops are ~50 mm in diameter (compared with 120 mm diameter fans on desktop computers), which means that they can only draw in small quantities of ash laden air. This air generally only travels a short distance through the fan and the heat sink before exiting, i.e. the air drawn in by the fan only travels over the heat sink and not over other internal components. This minimises the quantity of ash introduced into the laptop. In addition, cooling fans on laptops do not operate continuously and only turn on when the CPU is at a certain temperature (laptop dependant), again limiting the amount of ash that will be drawn in with the air. Air intake and exhaust holes are small and may have mesh covering them acting as filters, thereby limiting ash ingress. Additionally, as ash accumulates on top of, and around the sides of a laptop, it blocks all ash ingress points, which limits further ash ingress.

Ash also entered some laptops through the keyboard, depending on their design. Some keyboards had small holes through their base, which ash was able to fall through, others did not. Also, if the keyboard was being used at the time of ashfall, key pressing encouraged ash ingress through the keyboard.

The properties of the ash also affected ash ingress. When testing with moist ash, no ash was found inside laptops. This is because the wetter ash becomes the less mobile it is, due to its increased mass and tendency to form aggregate particles. Essentially, the moist ash fell onto and around a laptop and was not able to be drawn inside a laptop.

Ash distribution inside laptops was controlled by the design of the individual laptop (motherboard layout, cooling fan location and orientation, air intake and exhaust hole location, etc.) and the properties of the ash particles (primarily grain size and mass). Coarse ash particles were generally found near the edges of the laptop, as this was where most of the air intake holes were located. These coarse particles did not travel very far because of their large mass, compared to fine grained particles, and the low airflow within the laptop. Fine grained ash particles travelled further inside the laptops, forming thin coatings over components, as they are more mobile due to their low mass.

5.4.1.2. Vulnerable Components

The two most vulnerable components inside laptops were the CD drive and the cooling fan. These components are two of the four mechanical components within laptops, the other two being the hard drive, which is essentially sealed from the outside environment, and the keyboard, which is discussed in Section 5.4.3.

The CD drive was vulnerable to volcanic ash because there was a poor seal between the tray that holds the CD and the CD drive case, which allowed ash to penetrate the drive. If the CD drive is in use during ashfall, as was the case for these tests, the spinning CD will create air currents that will help draw fine ash into the CD drive. This ash can cover the lens, meaning that the laser underneath can no longer read the disk, which could be problematic if software is to be run off or recorded to a CD while the laptop is in the field during ashfall. Volcanic ash will also cover the CD, again making it difficult to read data off it, and may also cause abrasion to the disk causing permanent damage. Also additional weight added to the top of the laptop from ash accumulation can cause the thin metal CD drive case to deflect downwards, thereby pushing the CD into the lens causing large scratches on the CD. As computer manufacturers move their focus from CD to solid state data storage, laptop vulnerability will decrease.

Laptop cooling fans were vulnerable to jamming due to volcanic ash, because they were drawing ash laden air into the laptop on a semi-continuous basis. In addition, ash may fall into the fan through either the air intake or exhaust holes located next to the fan. The construction of cooling fans (Figure 5.8) allows ash to accumulate between the electromagnetic coil supports and the permanent magnet. This is because these two components are not sealed from the external environment for their own cooling purposes. Also, due to the static nature of volcanic ash, it can be attracted to these magnetic components. If enough ash accumulates between the electromagnetic coil supports and the permanent magnet, it can cause the fan to jam and stop working. This can lead to overheating of the CPU, as it now has no fan to draw away the hot air, which decreases performance in the short term and may lead to permanent failure of the CPU in the long term.

5.4.1.3. Laptop Computer Overheating

One issue that can cause reduced performance, restarts/shutdowns and/or permanent damage is CPU overheating. This occurred in three out of the ten laptops tested and resulted in a restart of two and shutdown of the other. Overheating was caused by jamming of the cooling fan (discussed in Section 5.4.1.2) and/or a reduction in airflow. During these tests, reduction in airflow was caused by two processes. Firstly, by blockages in the heat sink. Ash laden air that was drawn in by the cooling fans passed through the fins in the heat sink. Due to the small opening between the fins, any ash that accumulated there blocked the openings and reduced the heat sink's cooling efficiency. This led to abnormally high CPU temperatures. Secondly, overheating was caused by blockages of air intake and exhaust holes in laptop cases. During the ash tests large amount of ash accumulated on the top of and around the sides of the laptops. This ash blocked air intake and exhaust holes and limited the airflow through the laptop, causing it to operate at a higher temperature than normal. Also, the large accumulation of ash (<100 mm high) on top of and around the laptops caused an insulation effect, artificially increasing the temperature of the laptops.

5.4.1.4. Laptop Computer Resiliency

The lack of major damage (except to the CD drive and cooling fan mentioned in Section 5.4.1.2) to any of the laptops tested was again down to the design of laptop computers. When testing desktop computers, Gordon *et al.* (2005) found the most vulnerable components were the expansion card slots. These consist of two parallel rows (spaced ~2 mm apart) of Au plated Cu contacts mounted on the motherboard, which an expansion card (graphics, network, sound card, etc.) can be slotted into. Gordon *et al.* (2005) found that if moist ash bridged the connectors in the expansion card slot, it would create a short circuit and the computer would 'crash' and shutdown, i.e. 'a failure'. Due to the compact design of laptop computers, these types of slots do not exist on laptop motherboards as there is no space for them. This therefore limits the potential for ash to cause laptop failures. The connectors that hold RAM modules in place are similar to expansion card slots; however they generally have RAM modules plugged into them, removing the bridging potential. Also RAM modules are usually located well inside the laptop or behind protective covers. In addition, moist ash did not penetrate any laptops due to its poor mobility and the limited number of small openings in laptop cases. Other components (resistors, transistors, capacitors, etc.) attached to the motherboard were resilient to dry volcanic ash.

Another potential area for computer failure is in the power supply. Here, there is a potential for ash to cause short circuits leading to failure of the power supply and subsequently the computer. Desktop computer power supplies have large cooling fans and air intakes and are located inside the computer case, which means ash can easily enter, leading to damage. However, for laptop computers, the power supply is part of the power cord that is plugged into the laptop. This power supply is enclosed in an air tight plastic case which will prevent any ash entering it and no damage is possible.

5.4.2. Hard Drives

Hard drives did not fail during any of the ash tests as they are designed to keep all particles out, as any size particle can cause read failures. Hard drives work when a read/write head reads data off a rotating magnetic disk as it passes over it. The read/write head is kept ~3-4 nm above the disk (Xu *et al.*, 2006) due to a cushion of air forming above the rotating disk. Because of this, hard drive encloses are not designed to be airtight. A breather filter, which has an aperture of 0.3 μm (Mueller, 1998), allows the air pressure to equalise between the inside and outside of the enclosure while preventing particle ingress. Due to this small filter, none of the ash particles used were able to penetrate into the hard drive enclosure and cause damage.

Once the breather and vacuum filters were removed, ash was able to penetrate the enclosure and get stuck around the read/write head. Because the read/write head is extremely close the magnetic disk, any small particle can get stuck under it and prevent it from being able to read. No scratches were found on the magnetic disk.

5.4.3. Keyboards

The difference in performance of laptop and desktop keyboards is based on the design of the keyboard and keys themselves which differs slightly between the two types. The underside of keys on both types of keyboards are hollow, however, keys on desktop keyboards are higher than that of laptop keys and can therefore accommodate larger quantities of ash under the keys before it becomes difficult or impossible to push them down. Ash grain size is also important, as fewer large grains will be required to prevent the key from being depressed. It is also possible that some coarse grains of ash may get stuck between neighbouring keys thereby prohibiting key movement.

The mechanism by which the keys move for the two keyboards types is different, with laptop keyboards employing a scissor mechanism and desktop keyboards using a plunger mechanism (Figure 5.12). With the plunger design, more of the key is in contact with the keyboard base than with the scissor design, so any ash that gets trapped between the two moving pieces will limit its movement and eventually cause the key to jam. This was seen to a greater extent during cleaning, than during ash vulnerability testing. When a desktop keyboard was tipped on its side, a large number of ash particles became lodged between the key and the keyboard base, causing the keys to jam. Also the desktop keys overlap part of the keyboard base when fully depressed and any ash that collects here would cause these two components to become stuck together preventing the key from moving.

The scissor mechanism on laptop keyboards has more moving parts than desktop keyboards, however there is less surface area of the parts in contact with each other, therefore, it is less likely that these keys will become stuck as ash gets between these moving parts. In addition, laptop keys weigh less than desktop keys and the silicone dome has more force to push the key back up even if it is slightly stuck.

Once a laptop keyboard was removed from a laptop after ash exposure, it was significantly easier to clean than a desktop keyboard. This is because a laptop keyboard is not enclosed in a plastic case like a desktop keyboard is, and all its sides are open allowing the ash to exit. The only place ash can exit from a desktop keyboard is from around each key, and as this ash exits, some of it becomes stuck in the key plunger, requiring the key to be removed to clean around it, which is time consuming.

These ash vulnerability experiments were undertaken with slightly older style keyboards, and there are now some new key designs on the market for both laptop and desktop keyboards. Some new laptop keyboards use keys that are spaced further apart, which would allow more ash to get under the keys, decreasing their functionality. Other laptop keyboards use a chiclet or isolation design (Figure 5.13), in which keys have straight edges making them a square shape, allowing keys to be placed further apart. A perforated cover is place over the gaps between the keys. The small gap between the keys and cover would limit the amount of ash that could get under the keys, however, each key is isolated so if ash did get under the key it would be very difficult to clean, and it would be likely that each key would need to be removed individually for thorough cleaning. Some new desktop keyboards have low profile keys (Figure 5.14), which are approximately half the height of older style keys and are a similar height to the laptop keys used in these experiments, although the plunger mechanism is still used. These smaller keys would mean less ash could fit under them leading to a reduction in key functionality, if affected by ash, similar to the laptop keyboards in these experiments.

Figure 5.13: Chiclet key design on a laptop computer keyboard (from www.netbooklive.net).

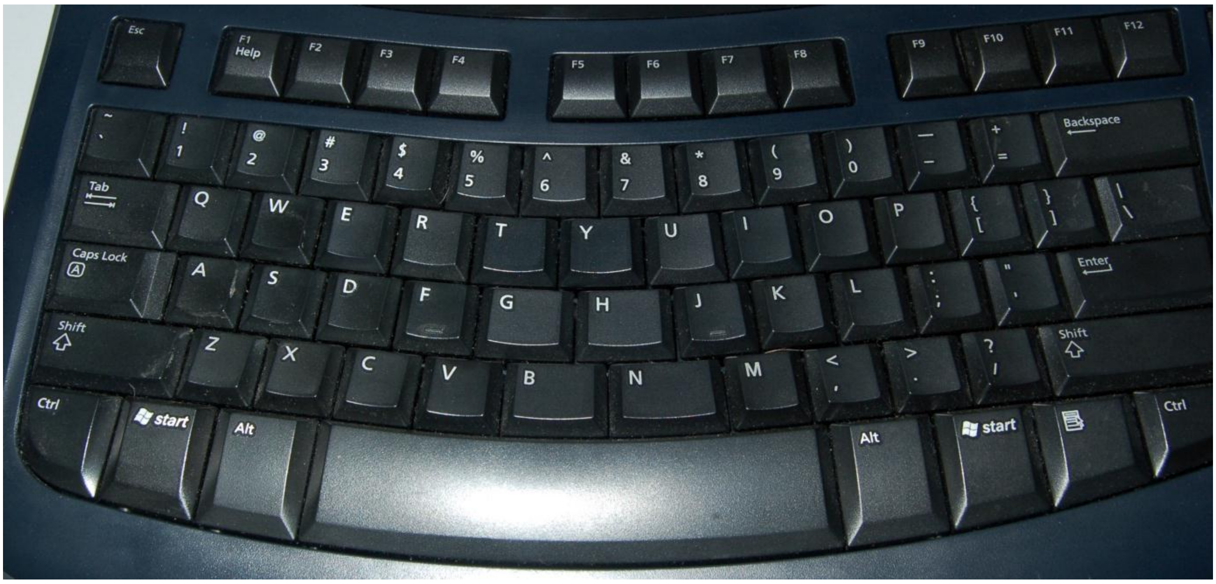

Figure 5.14: Low profile key design on a desktop keyboard.

5.5. Mitigation Techniques

Reducing the vulnerability of laptop computers to volcanic ash and gas hazards can be achieved through the use of mitigation techniques.

Mitigation techniques may take the form of:

- limiting exposure to volcanic hazards by reducing the amount of time laptops are in the field.
- protecting laptops from the hazards.
- thoroughly cleaning laptops once returned from the field.

The most effective and simple way to reduce laptop computer's risk from volcanic hazards is to limit its exposure to them. Ideally, a laptop would only be taken into the field if specifically required for data gathering and only remain in the field for as long as needed. Even with limiting the exposure, a laptop may have ash and gas deposited onto it, which may reduce its functionality. This is where cleaning of laptops becomes important. Once a laptop has come back from the field it should be thoroughly cleaned with compressed air, a vacuum cleaner, a damp cloth, contact cleaners, etc. This will prevent ash clogging up components and prevent the possibility of long term corrosion occurring due to acids from the ash and gas.

For long term use of laptops in the field, the best mitigation techniques (MT) available are the use of protection methods, which seal laptops from ash and gas exposure. As part of this research, three protection methods were tested (Figure 5.15), these were:

- MT1 – sealing a laptop with polyethylene sheeting, duct tape and vacuum cleaner air filters.
- MT2 – placing a laptop inside a mesh fabric laptop carry bag.
- MT3 – placing a laptop inside a heavy duty polyethylene sample bag and duct taping it closed.

These methods were chosen as they were simple, cost effective, and retained laptop functionality. The laptops used for the mitigation testing had the same BurnInTest™ setup as used for the ash vulnerability testing (Section 5.2.2).

The laptop which used MT1 feared the worst out of the three methods, as ash was still able to penetrate the laptop. Small quantities, approximately the same as was found in the unprotected laptops, was found on the motherboard. This ash was able to get in between joins between the screen, keyboard and laptop case, as holes had to be made in the polyethylene sheeting to allow these components to be attached to the laptop. In addition, this method took the longest amount of time to implement.

Ash was not able to penetrate the laptops which used MT2 or MT3. While being exposed to ashfall, these laptops operated normally. One advantage of MT3 over MT2 was that the ash was easier to clean off the polyethylene bag than the fabric bag. During testing, ash was able to collect between the weave in the fabric making it difficult to clean. This could be problematic if the carry bag was to be taken into a clean office environment or used for another purpose. Another advantage of the polyethylene bag is it is a lot cheaper than a fabric laptop carry bag.

Figure 5.15: Two mitigation techniques (A) laptop protected with plastic sheeting on keyboard and duct tape over all joins; and (B) laptop protected inside a heavy duty polyethylene bag.

The main limitation of these two methods (MT2 and MT3) was that the laptop needed to have its lid closed in order to fit inside the bags. This reduced the laptops functionality and usability as the keyboard, mouse pad and screen could not be used while being tested. However, it is possible to obtain a very large heavy duty polyethylene bag that can accommodate a laptop with its lid open. This would restore function while still protecting the laptop.

While MT3 was not tested in a volcanic gas environment, it is likely that it will work just as effectively as it does for volcanic ash. This is provided the polyethylene is impermeable to gas and the opening is sealed effectively. A fabric carry bag (MT2) is not likely to do as well, due to the permeable nature of the fabric and the zip.

Most volcanic observatories surveyed for this thesis (Section 3.3) do use some combination of the above mitigation methods, and this is reflected by the lack of laptop damaged reported by these organisations.

It is highly recommended that these mitigation methods (limiting exposure, cleaning once returned from field and protecting laptops by placing them inside a polyethylene bag) be implemented whenever a laptop is taken into a volcanic environment for any amount of time. This will not only reduce the risk of damage in the short term, but over the long term as well. These methods can also be applied to any other electronic equipment that is taken into the field.

5.6. Limitations

The two limitations of this ash vulnerability testing was that: not all ashfall parameters (ash thickness and grain size) for all laptop components were tested; and no medium or long term volcanic ash vulnerability tests were carried out. These limitations arose due to time constraints, limited test components and the fact that some components were difficult to test individually. However, taking into account these limitations, the data produced during these experiments provides a good first estimate as to how laptop computers will be affected by volcanic ash hazards.

Chapter Six – Analysis of Volcanic Gas Impacts to Laptop Computers

6.1. Introduction

The objective of this testing was to determine the vulnerability of laptop computers and printed circuit boards (PCBs) to short term acute volcanic gas hazards. It was established in the risk analysis stage (Section 2.3.2) that this has received little attention in the volcanology community, with the primary focus on long term chronic gas hazards (e.g. Durand and Scott, 2005; Durand, 2006). Laptop performance and functionality was sought in order to develop functionality functions and risk reduction strategies for volcanic gas hazards.

Short term testing was favoured over long term due to its simplistic set up. Time and funding constraints also prevented long term testing from being undertaken. However, questionnaires delivered to businesses in Rotorua and international volcanic observatories (Chapter Three) provided some data regarding long term gas hazards.

The experiments were designed to simulate a maximum credible event, of electronic equipment left unprotected in close proximity to highly active volcanic fumaroles. This scenario is applicable to the use of volcanic surveillance equipment in volcanic gas environments.

6.2. Test Set Up

6.2.1. Location

White Island, New Zealand was chosen as the test location as it is an easily accessible gas rich volcanic island. White Island is an active stratovolcano situated 48 km off the Bay of Plenty coast, north of Whakatane, and is near the northern end of the TVZ (Spinks *et al.*, 2005) (Figure 6.1). Numerous craters and fumaroles on the island continually emit volcanic gases, such as CO_2, H_2S and SO_2, at rates of several hundred tonnes per day (Rose *et al.*, 1986).

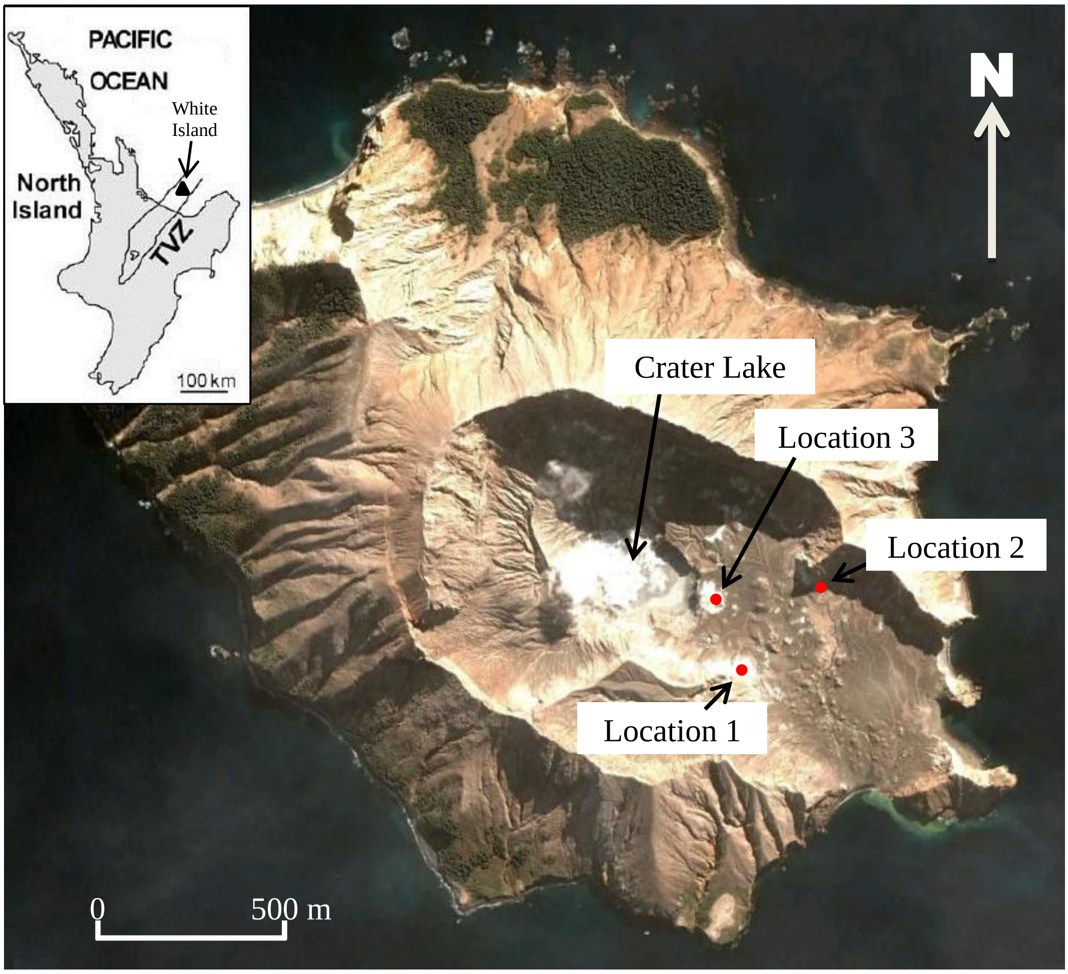

Figure 6.1: Aerial view of White Island showing laptop and PCB testing locations (from Google Earth). Location 1 has two highly active fumaroles; location 2 has a medium activity fumarole; and location 3 has a low activity fumarole. Inset shows the location of White Island offshore of New Zealand's North Island (modified from Durand and Scott, 2005).

6.2.2. Laptop Computers

Three laptop computers were deployed on White Island on 23 February 2010 by the author, as a guest on a routine GNS Science surveillance trip. The laptops (laptop 2, 4 and 7) all had similar specifications (Appendix D). As with the ash vulnerability testing, the laptops had Microsoft® Windows® XP operating system, PassMark® BurnInTest™ V6.0 Pro and SpeedFan software installed (Section 5.2.2).

The laptops were placed within 2 m of three different fumaroles, which ranged from high to low activity (Figure 6.1). This close proximity simulated the worst-case scenario for surveillance equipment, if it was to be used to monitor fumarole discharge. The laptops were left on the island for approximately five hours, as this was the duration of the GNS Science surveillance trip.

For the first two hours of exposure, the laptops operated on their internal battery, as there is no electricity supply on White Island. Once the battery power ran out the laptops shutdown and continued to be exposed to volcanic gases for three hours before being removed from the island. While the laptops were on, the BurnInTest™ software stress tested the laptop's hardware by completing various calculations, and was used to simulate normal use. Also running was the SpeedFan software which recorded the laptop's internal temperature to determine if it was overheating at any point during the experiment. Both of these programmes saved their log files to external USB flash drives which were protected with masking tape and connected to the laptops via a USB extension cable. This was done to prevent loss of data if the laptop's hard drive failed during the experiment, as it was more likely that the mechanical hard drive would fail before the non-mechanical flash drive.

Prior to this vulnerability experiment, photographs were taken of the laptops internal components in order to provide a comparison to post exposure photographs.

6.2.3. Printed Circuit Boards

Nine PCBs were deployed to White Island on 12 January 2011 as part of a University of Canterbury research trip to the island assisted by the Royal New Zealand Air Force. The PCBs were deployed to the same locations as the laptops (Figure 6.1) and were exposed to volcanic gases for ~26 hours, as this was the duration of this research trip.

The PCBs were desktop computer expansion cards and were of similar design, with component layout being the only difference. This type of PCB was used because they were easily obtainable and contained a range of electronic components. The boards were mounted on wooden frames in groups of three (Figure 6.2) and directly exposed to volcanic gases, i.e. they were not connected to computers and therefore did not have their usual protective casing. This was done to analyse a worst-case scenario were a PCB was not protected from volcanic gas exposure. Also attached to the wooden frames, ~20 cm off the ground were three Gastec Passive Dosi-Tubes used for measuring time-weighted mean gas concentrations of CO_2, H_2S

and SO_2 (tubes used were: No. 2D for CO_2, 0.02-12% over 0.5-10 hours; No. 4D for H_2S, 0.2-200 ppm over 1-48 hours; and 5D for SO_2, 0.2-100 ppm over 1-10 hours).

Like the laptops, photographs of the expansion cards were taken before vulnerability testing. In addition to this, SEM photos were taken using an FEI Quanta 200F SEM with energy-dispersive X-ray spectroscopy (EDS) capabilities at the University of Auckland, to view corrosion products in detail. EDS plots were also produced providing the chemistry of corrosion products.

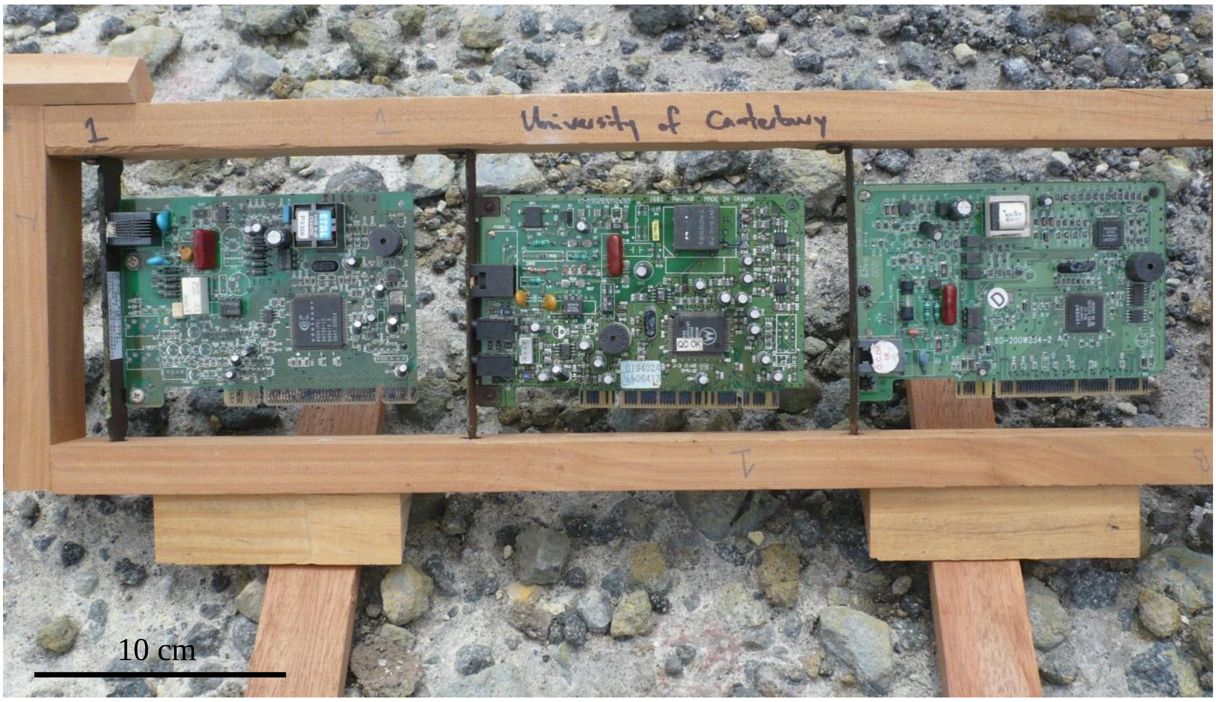

Figure 6.2: PCBs mounted in a wooden frame on White Island. This photo was taken after 26 hours of exposure to volcanic gases.

6.3. Results and Discussion

6.3.1. Laptop Computers

The BurnInTest™ log files showed that the laptops operated normally throughout the exposure test and that no errors occurred (Appendix F). SpeedFan indicated that the laptops operated at approximately the same temperatures during the experiment as prior to gas exposure (Appendix F). A repeat stress test the following day confirmed normal operation with no BurnInTest™ errors.

Laptop 2, which was at location 1 in Figure 6.1, showed the most noticeable effects of exposure to volcanic gases. This was because this laptop was downwind of the two most active fumaroles on White Island. The laptop showed signs of minor corrosion of the Cu heat sink (Figure 6.3 A); the Cu around the CD drive (Figure 6.3 B); the stainless steel around the external connectors (USB, screen and parallel ports); and some of the stainless steel inside the case under the motherboard (Figure 6.3 C). The corrosion observed was cosmetic and did not affect the operations of the components or laptop as a whole.

This laptop also had precipitated droplets of H_2SO_4, from the fumarole gas plume, on the screen; keyboard; and mouse pad (Figure 6.4). Again, this was only cosmetic and did not affect the laptop's operation. As of August 2011, this laptop was still operating normally producing no errors when subjected to a stress test.

Laptop 4 and laptop 7 (location 2 and 3, respectively in Figure 6.1) showed no corrosion of any internal components and only had very minor, cosmetic corrosion to the external connectors. The likely reason for the lack of corrosion on these two laptops was because, laptop 4 was upwind of a fumarole, as the downwind side was too dangerous to get to, and laptop 7 was next to a low activity fissure vent.

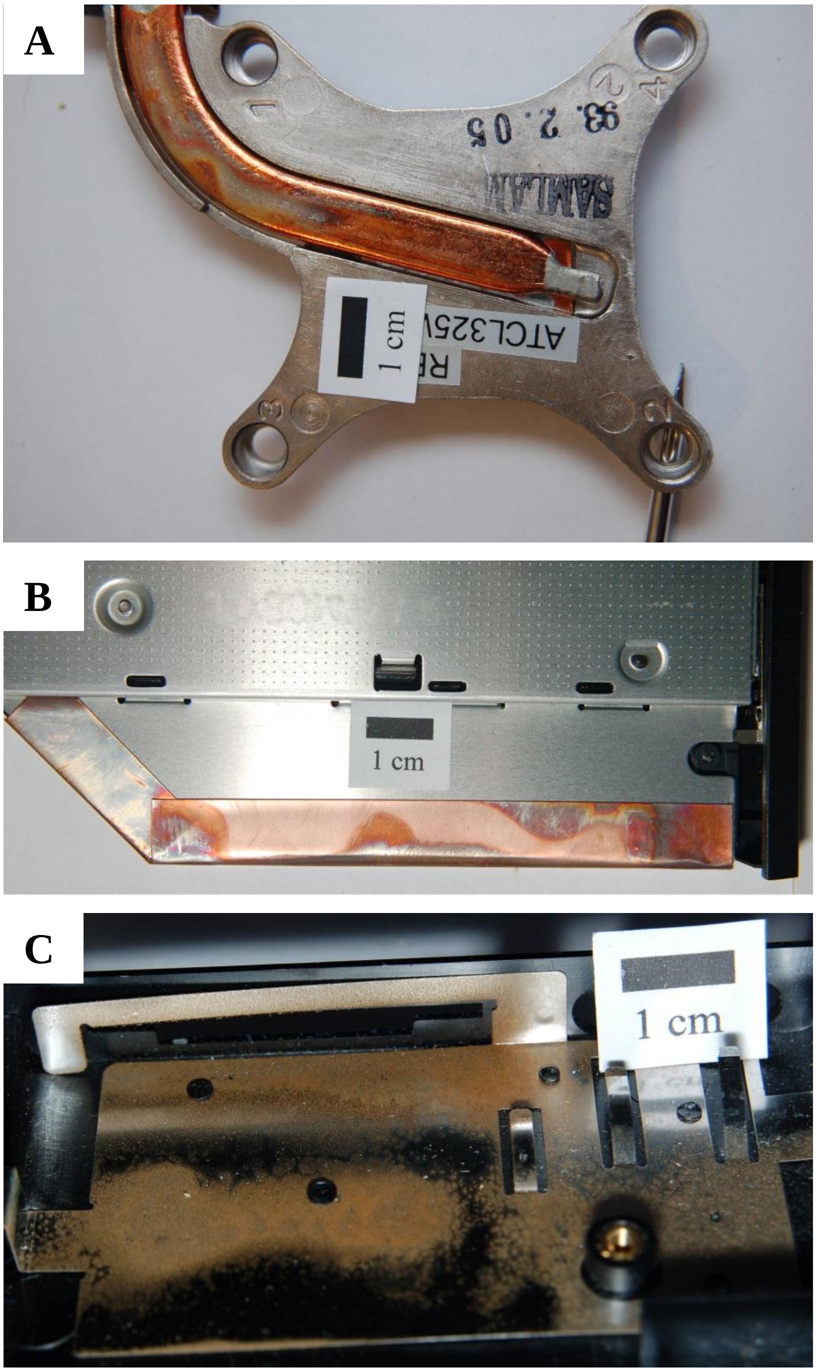

Figure 6.3: Photographs showing minor corrosion on laptop 2 after exposure to volcanic gases. (A) corrosion on heat pipe on CPU heat sink; (B) corrosion on Cu tape surrounding CD drive; (C) corrosion (rust) on stainless steel inside computer case.

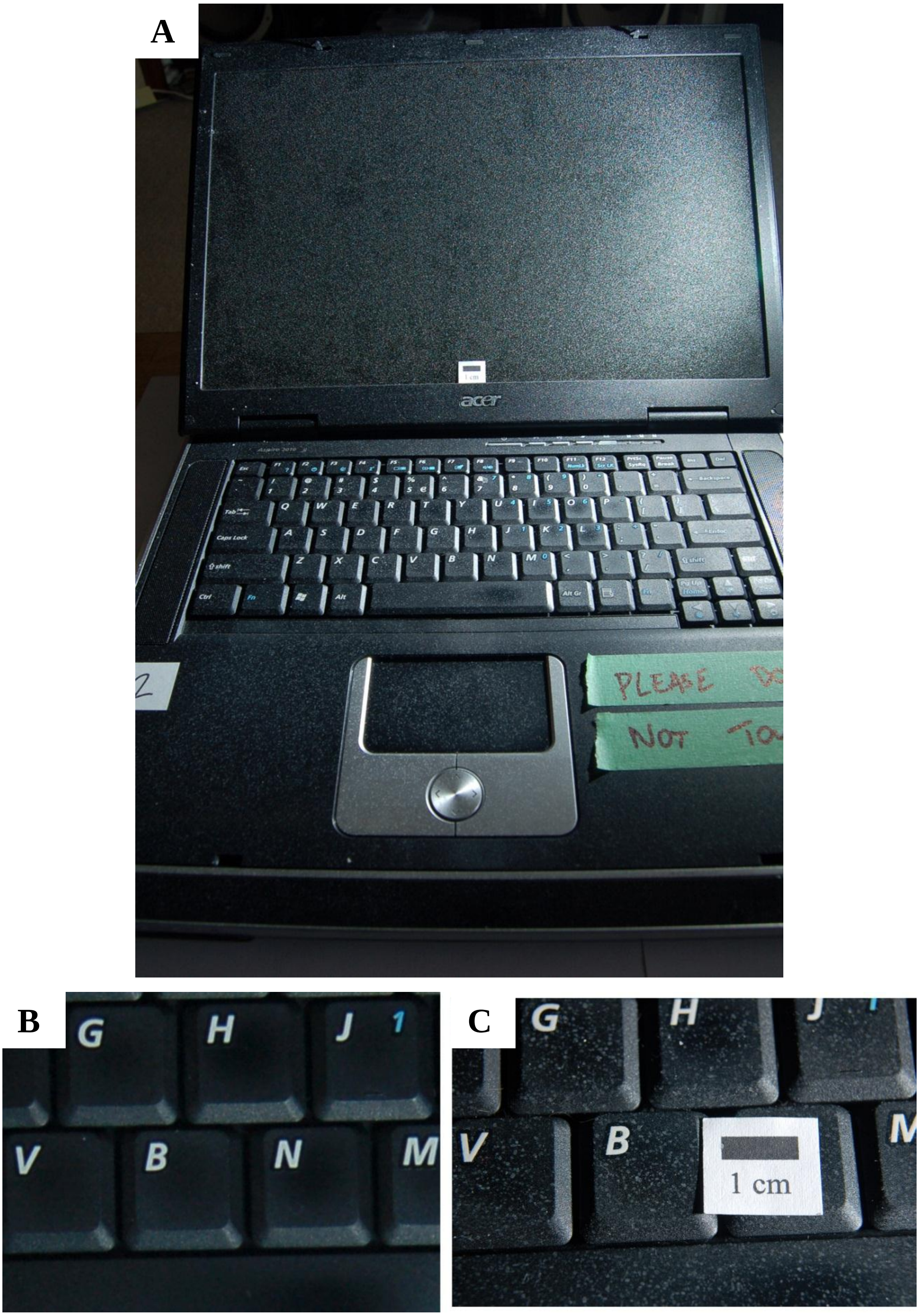

Figure 6.4: Photographs of laptop 2. (A) extent of covering of precipitated H_2SO_4 droplets (white dots) after exposure; (B) keyboard before exposure; and (C) keyboard after exposure.

An unanticipated result came from the USB cables that were used to connect the USB flash drives to the laptop computers. The cables showed some minor corrosion on the plug end (Figure 6.5), even though they were inside the receptacle port on the laptops during the tests. One year after the gas vulnerability experiments, these cables have become slightly more corroded, forming a thin rust layer. However, the cables still worked, without loss of performance, when used for other experiments.

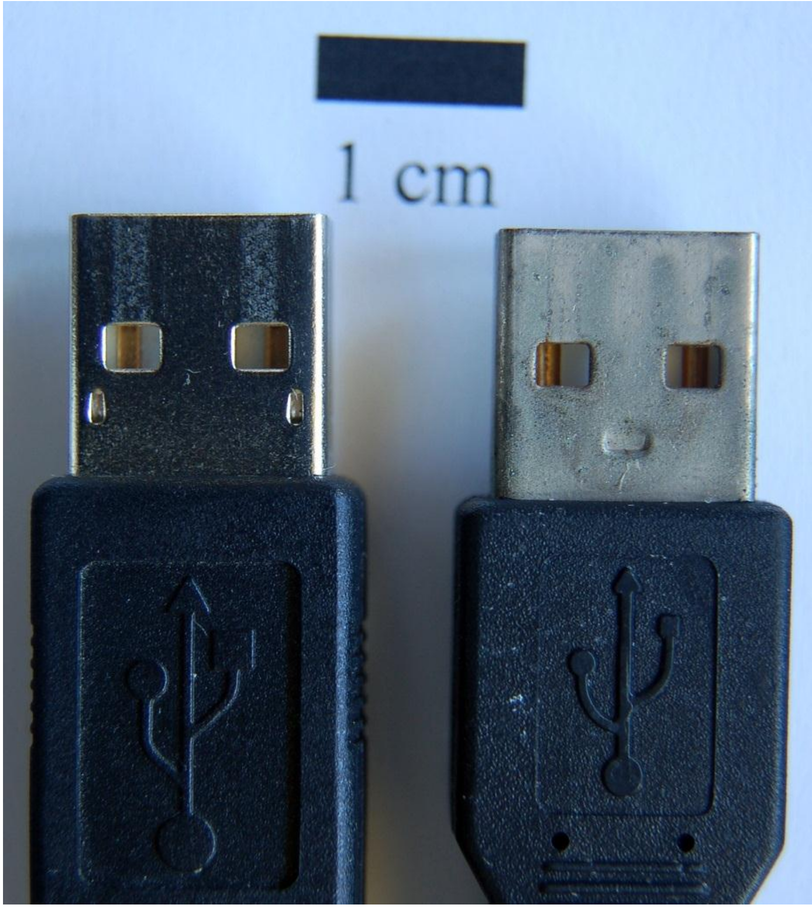

Figure 6.5: Photograph showing a 'near new' USB cable plug on left and an exposed plug on right.

These results suggest that severe corrosion of laptop components does not occur over short time periods. The limited corrosion observed is due to volcanic gases not being able to get inside the laptops where it could cause severe corrosion. This is because laptop computers have very few small ventilation holes in the case, which prevents large quantities of gases entering the case. The three components (CD drive, heat sink and card reader) that did sustain minor corrosion were located next to holes in the laptop case, allowing volcanic gas to corrode them. However, the more important and sensitive components, such as the motherboard, RAM and hard drive are located in areas where there are fewer case openings, preventing gas from corroding these components.

6.3.2. Printed Circuit Boards

All nine PCBs sustained corrosion during the vulnerability experiment. The three boards that were at location 1 (Figure 6.1) sustained the most corrosion (Figure 6.6), due to the two highly active fumaroles at this location. The concentration of volcanic gases on White Island during the tests are given in Table 6.1.

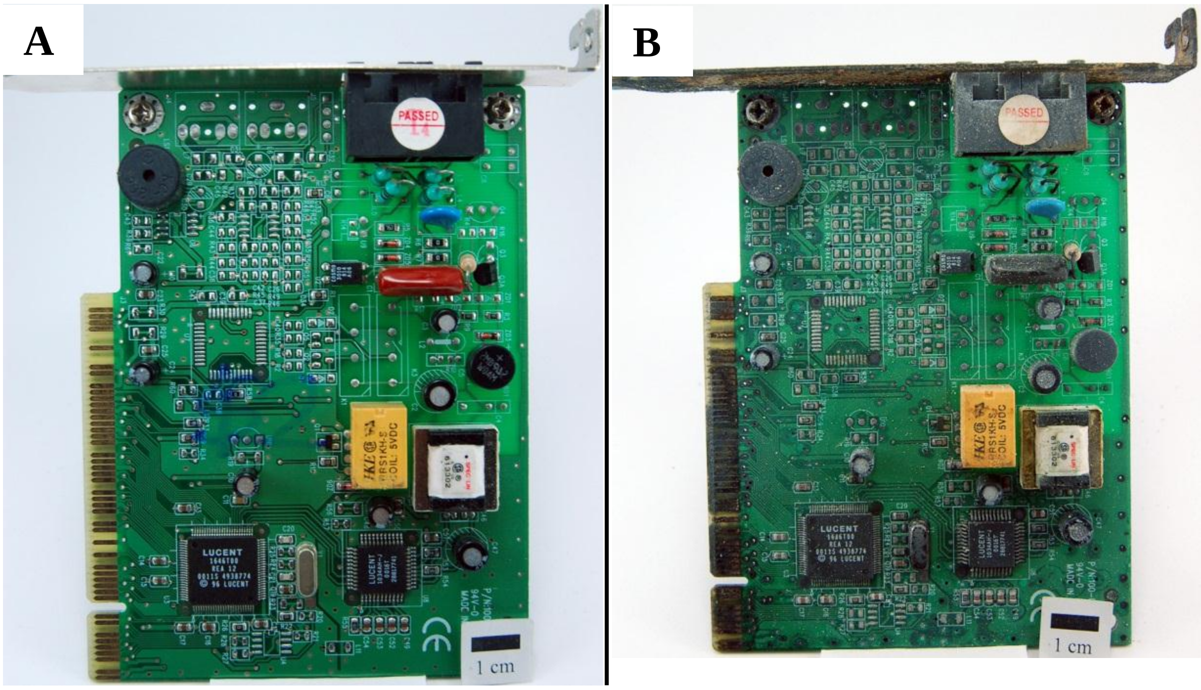

Figure 6.6: Photographs of PCB from location 1. (A) card before exposure to volcanic gases; (B) card after exposure.

Table 6.1: Concentration of CO_2, H_2S and SO_2 from Dosi Tubes place on White Island from 12-13 January 2011 (~26 hours).

Gas	Minimum	Average	Maximum
CO_2	0.10%	0.16%	0.23%
H_2S	1.00 ppm	7.30 ppm	16.7 ppm
SO_2	3.70 ppm	3.70 ppm	3.70 ppm

Various components, such as Au plated Cu/Ni edge connectors, capacitors, and solder, on the expansion cards at location 1, sustained significant corrosion. The Au plated edge connectors that are used to connect the card to a computer, were completely covered with a black corrosion product (copper and/or nickel oxide) and small green crystals (copper and/or nickel chloride) (Figure 6.7 and 6.8). Cu and Ni corrosion products have formed because the Au plating is relatively porous, which allowed the volcanic gases to react with the Cu and Ni underneath. These corrosion products are resistive and caused the computer to fail to turn on when the PCB was plugged in (i.e. the card lost all of its functionality). The Cl present within the copper and/or nickel chloride corrosion product was derived from volcanic gases present on White Island. Small quantities (1.25 wt%) of Sn was also found on the connectors and is likely to have come from the solder that is used on PCBs, which is lead (Pb) free nowadays, hence why no Pb was found with the Sn. It is possible that sulfur compounds (copper and/or nickel sulfide) were present on the edge connectors, as they were found on the PCB itself; however the Au peak on the EDS plot (Figure 6.8) is obscuring any sulfur peaks.

Exposed metal on the top of all capacitors was moderately corroded, and in one case, one of the capacitors was so severely corroded it fell off the PCB when touched. The capacitors are protected by a hard polyethylene terephthalate layer which has suffered some discolouration obscuring the specification markings. Furthermore, the solder attaching most of the components to the card was mildly corroded. The most severely corroded part of the cards was the back mounting plate (Figure 6.9). This stainless steel plate had undergone exfoliation corrosion, where the layers of metal peel off as it corrodes. However, this does not affect the functionality of the PCB as it is only used to hold the card in place inside a computer.

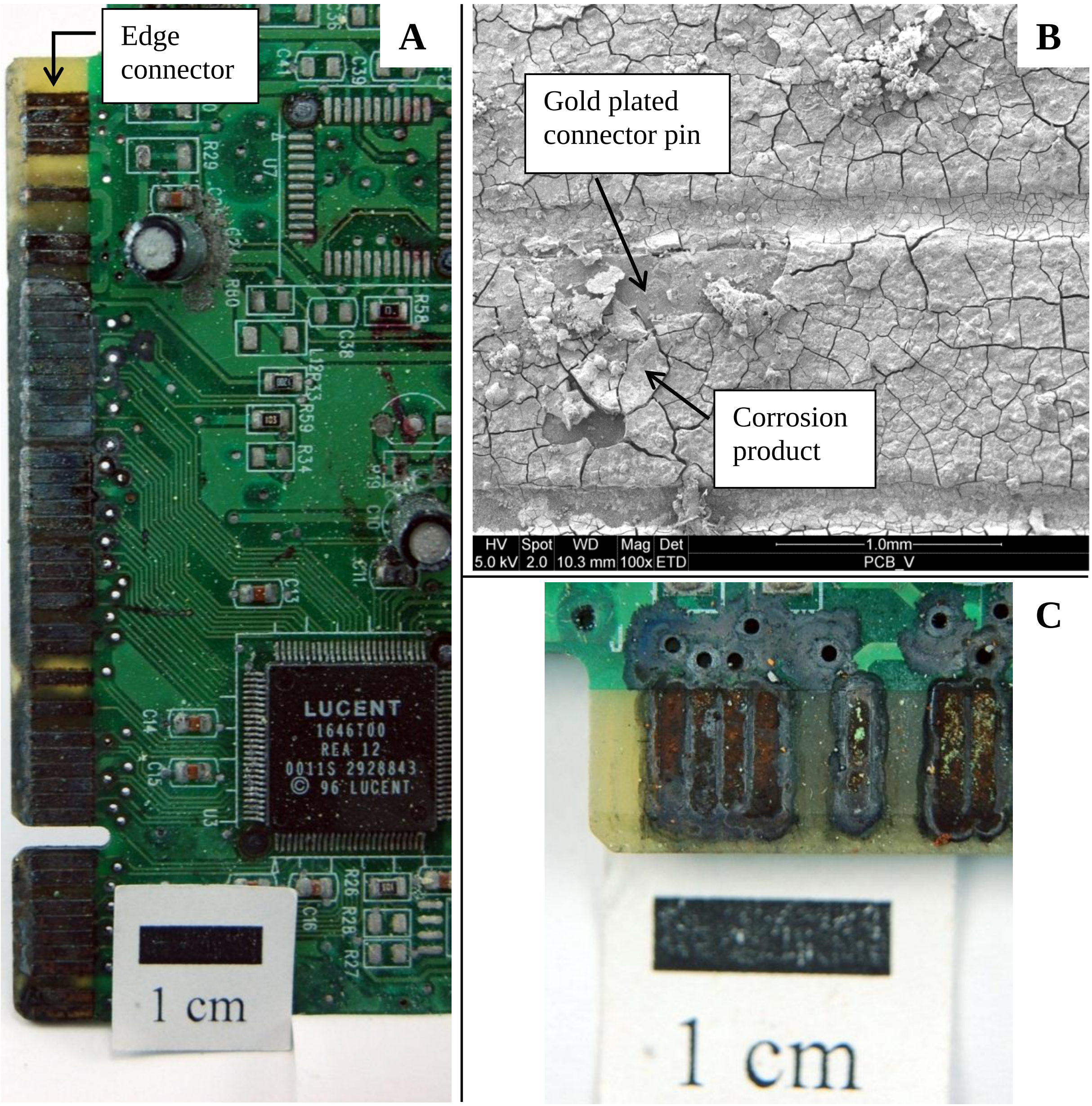

Figure 6.7: Photographs of an exposed PCB from location 1. (A) photograph showing the corroded edge connector; (B) SEM photograph at 100 times magnification showing the corrosion product forming a layer over the Au plated connector pin; and (C) close up of seven edge connector pins and 'through holes'.

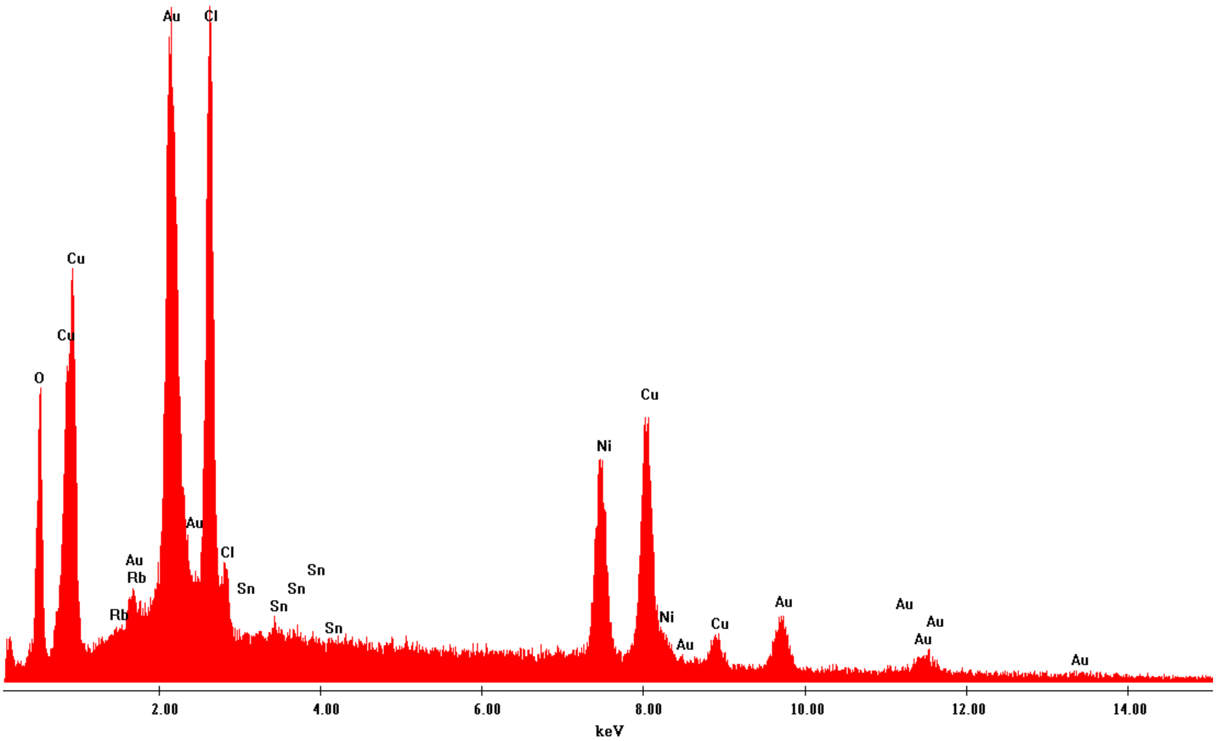

Figure 6.8: EDS plot of a point on a gold plated connector on an exposed PCB from location 1. Au, Ni, Cu are from the connector, Sn is from the solder, Cl is from volcanic gases.

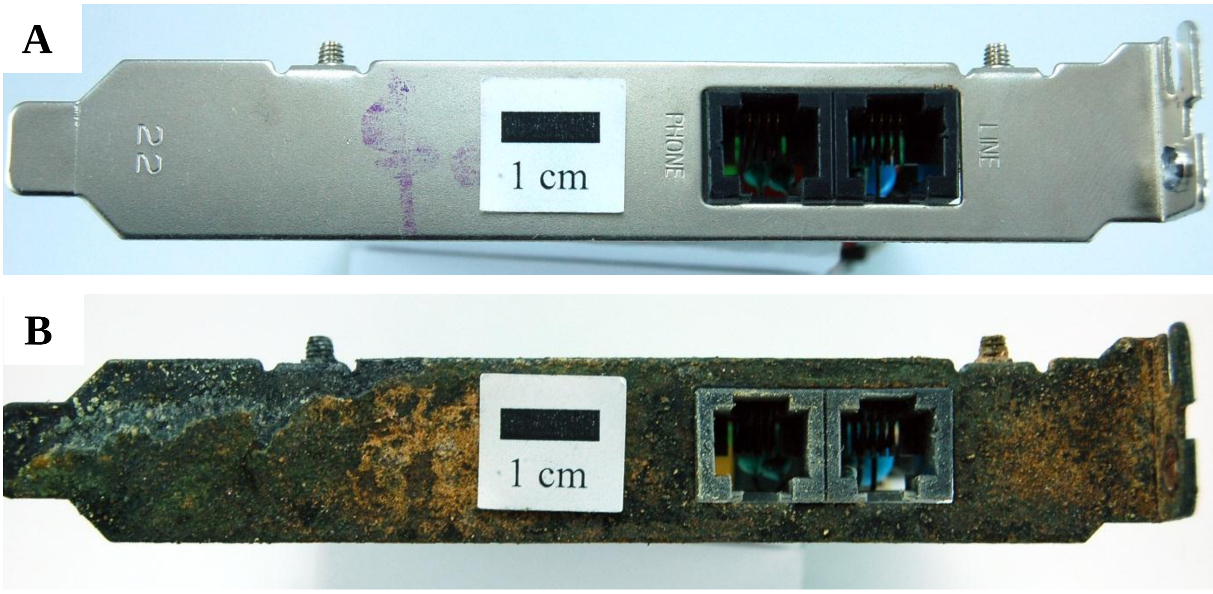

Figure 6.9: Photograph showing the PCB back mounting plate from location 1 (A) before exposure and (B) after exposure.

In addition to the corrosion of the metal components, the circuit board itself was affected by the volcanic gases. This is because the board is relatively porous, which allowed gas to permeate into the PCB and react with the various layers. EDS plots (Figure 6.10), indicated that bromide (Br), which is used on PCBs as a flame retardant (Alaee *et al.*, 2003), was removed from the board after exposure. In addition, Cl and sulfur (S) were deposited onto the board after exposure as a result of deposition from the volcanic plume. PCBs also contain a number of ‘through holes’ which connect the different layers together. These are commonly lined with Cu, and after exposure were corroded, forming the same black corrosion product that was found on the edge connectors. Also, the area immediately around these holes was darker in colour than the rest of the board, indicating that gas had permeated into the PCBs layers via the ‘through holes’ and possibly altered the PCB substrate. In some places the corrosion product from the edge connectors had been deposited onto the board, indicated by the Cu and Ni peaks in the EDS plot (Figure 6.10).

The six expansion cards at locations 2 and 3 had corrosion in the same places as those at location 1, but to a lesser extent. Like the laptop computers, this was because these cards were located close to fumaroles that were less active than the two at location 1.

These results show that without any protection, computer PCBs will corrode in volcanic gas environments, in a relatively short time frame, losing all functionality. When comparing these results to those from the laptop vulnerability experiment, it is clear that the protection provided by the laptop’s plastic case is enough to prevent significant corrosion of its components.

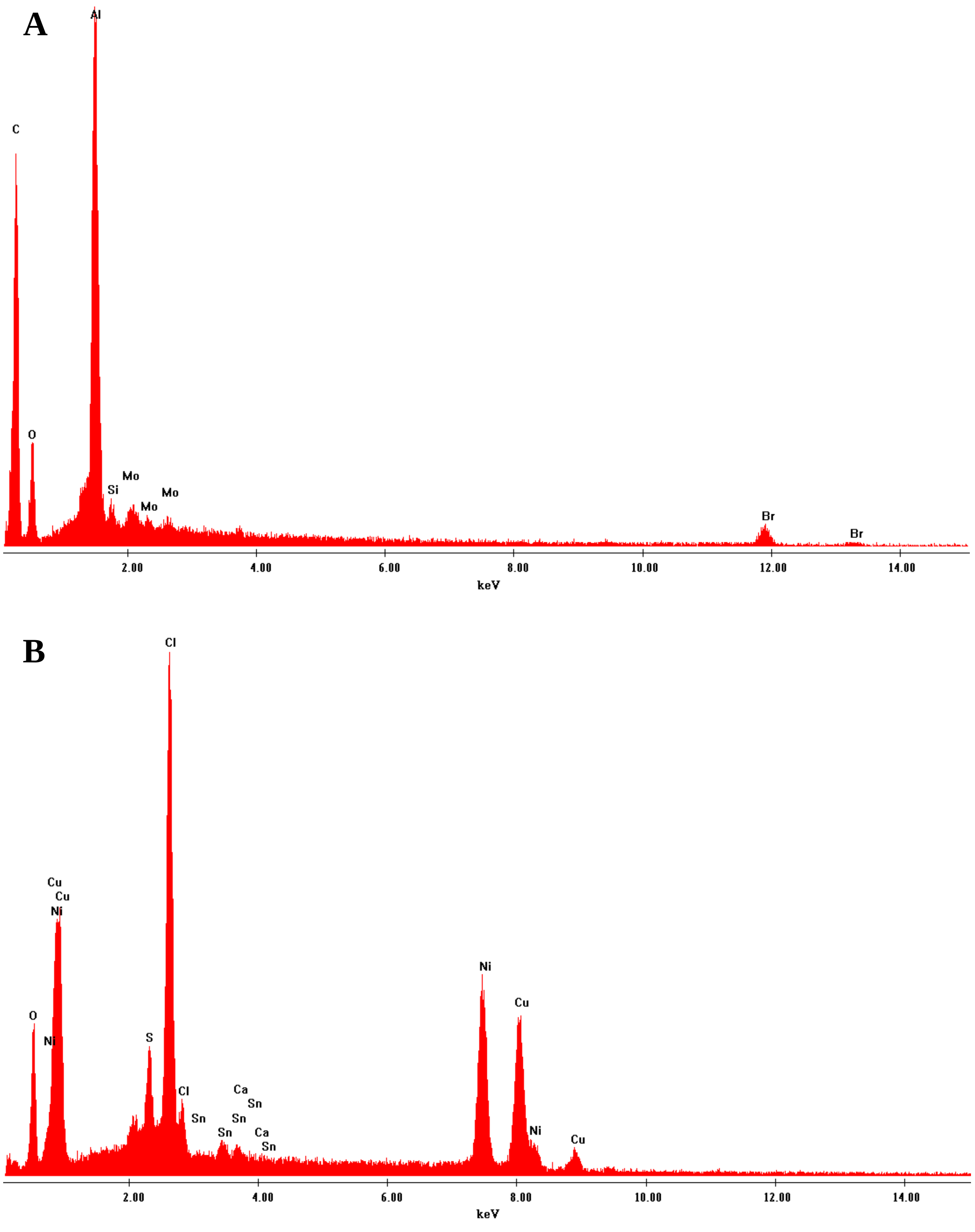

Figure 6.10: EDS plots of a point on the circuit board of a PCB from location 1. (A) before exposure to volcanic gases; and (B) after exposure.

Chapter Seven – Vulnerability Assessment

7.1. Introduction

The goal of this chapter was to assess the vulnerability of laptop computers to volcanic ash and gas hazards. Experimental results show that laptops did not sustain any permanent damage after being exposed to volcanic ash and gas hazards over short timeframes. However a number of components within the laptop reduced in functionality, as hazard intensity increased, causing a reduction in laptop functionality as a whole. The results of this research can be used to assess functionality both quantitatively and qualitatively through the use of functionality functions, scenario based event trees and risk tables.

7.2. Functionality Functions

The derived functionality functions show how the functionality of laptops, as a whole, (Figures 7.1 and 7.2) and the individual components (Figures 7.3 and 7.4) change, as the volcanic ash hazard intensity increases. These are a useful way to assess risk, as they are solely derived from empirical experimental data, in which all hazard intensities can be examined in a controlled environment. These functions can be used as a guide in volcanic ash environments to assess how laptop computers will likely function and whether protection is required.

Functionality was calculated by the percentage change in the number of calculations, carried out by the various laptop components as recorded by the stress testing software, between pre ash vulnerability tests and during ash vulnerability testing (Appendix F). In the case of the keyboards and mouse pads, functionality was calculated by the percentage change during usability tests (Figures 5.10 and 5.11). Functionality, on these plots, ranges from 0-100%, where 0% indicates no functionality of that component and 100% indicates full functionality. Overall laptop functionality in Figures 7.1 and 7.2 is an average of component functionality from Figures 7.3 and 7.4.

Figure 7.1 shows how the functionality of a laptop decreases exponentially as ash grain size increases from 0 to 800 μm, for ash thicknesses of 2 mm. Functionality decreases gradually for grain sizes <500 μm, after which functionality remains constant at ~75%. This indicates that fine ash particles have the biggest impact on laptop functionality, as these smaller particles are able to penetrate into the laptop more effectively than large particles (>500 μm). Also shown is a linear function for when a laptop is fully protected from the volcanic environment. This function is constant at 100% functionality, as no ash will be able to penetrate the laptop while fully protected.

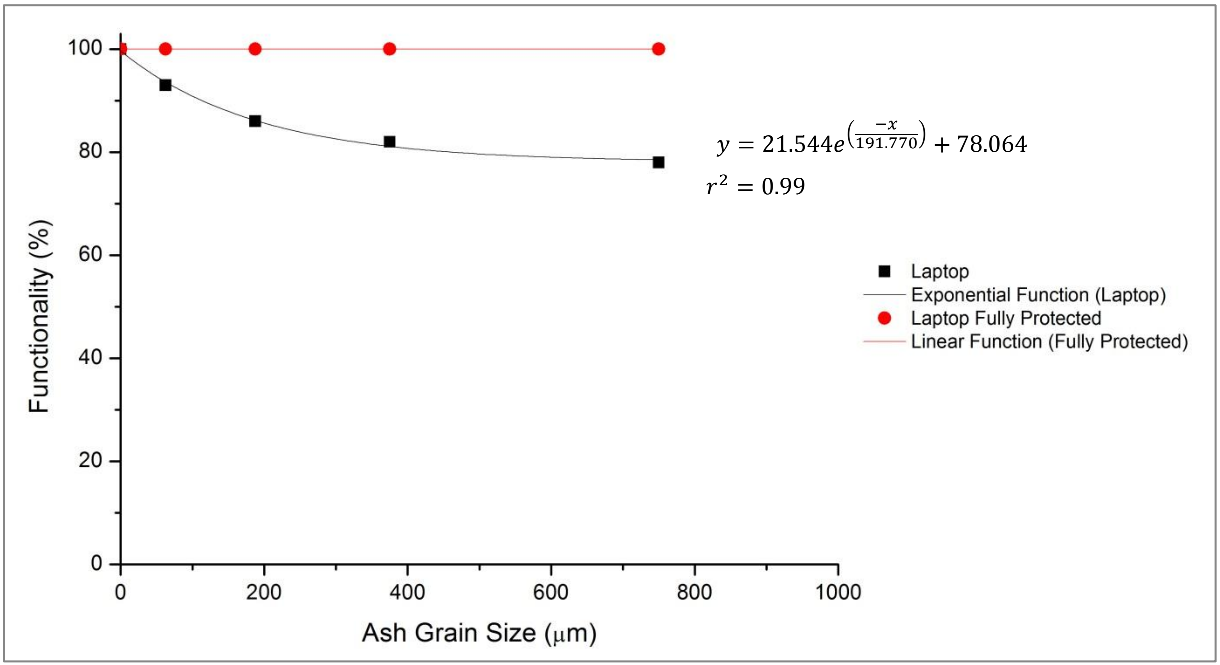

Figure 7.1: Laptop component functionality functions for different ash grain sizes at 2 mm thickness.

Figure 7.2 shows how laptop functionality decreases exponentially as ash accumulation thickness increases from 0 to 100 mm, for ash grain sizes between 250-500 μm. Functionality decreases rapidly from 100% to ~70% for ash thicknesses <10 mm, and remains constant at ~70% for thicknesses >10 mm. This is because at thicknesses >10 mm, ash piles around the case begin to block ventilation holes in laptop cases, preventing further ash ingress, effectively protecting the laptop. Again a liner trend is shown for when a laptop is fully protected.

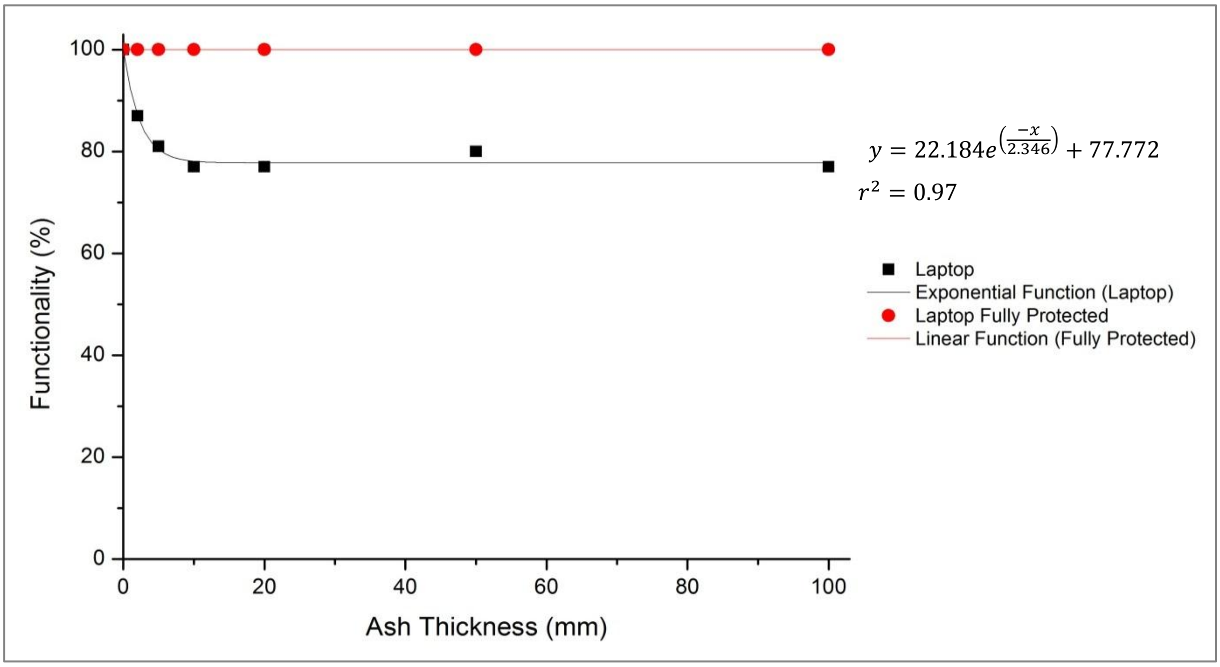

Figure 7.2: Laptop functionality functions for different ash thickness with grain sizes of 250-500 μm.

Figures 7.3 and 7.4 show functionality functions for individual laptop components for changes in ash grain size and thickness, respectively. Constant linear functions at 100% functionality exist for the CPUs, hard drives, mouse buttons and motherboards as ash either does not get inside the component or does not affect their operation. The functionality of the other components (CD drives, keyboards and mouse pads) decreases exponentially, to varying degrees, as ash grain size and thickness increase.

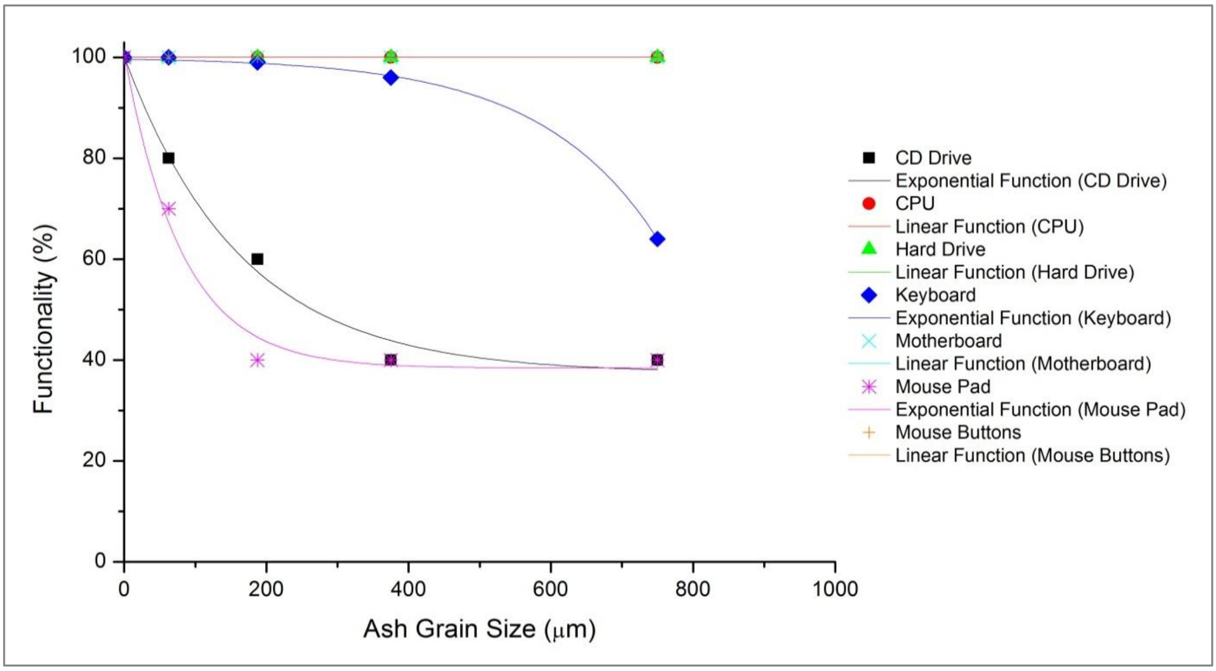

Figure 7.3: Laptop component functionality functions for different ash grain sizes at 2 mm thickness.

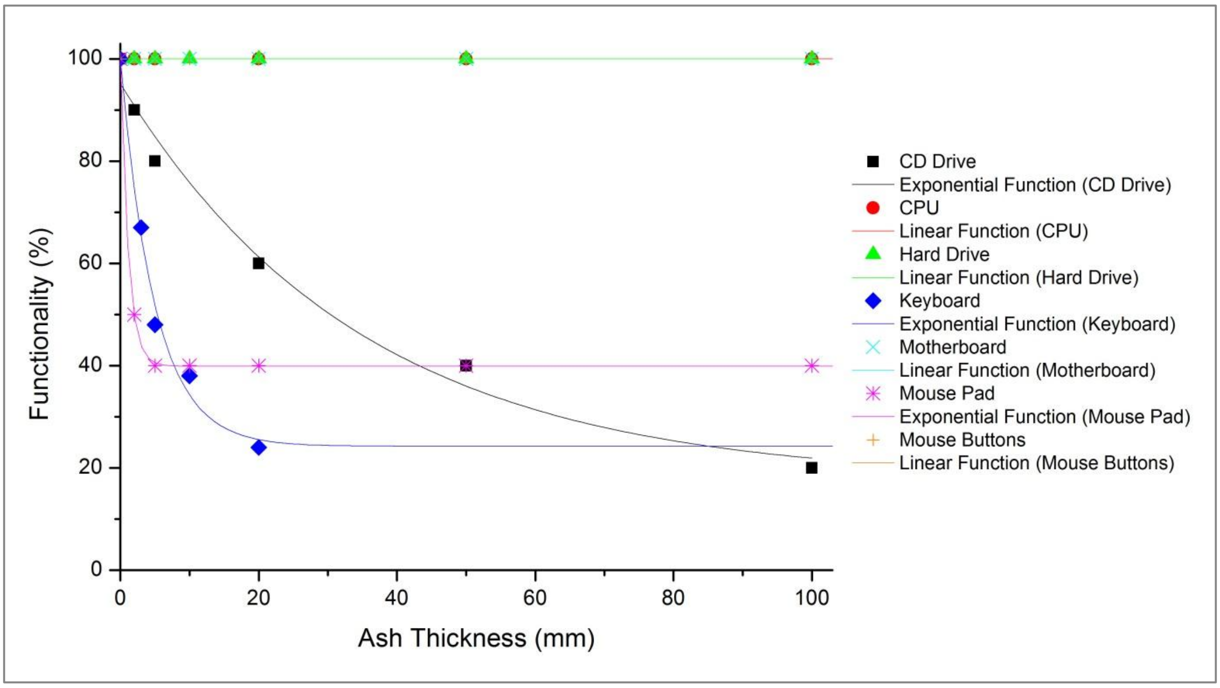

Figure 7.4: Laptop component functionality functions for different ash thickness with grain sizes of 250-500 μm.

7.3. Qualitative Assessment

In addition to the above functionality functions, a qualitative assessment has been made in the form of risk tables (Tables 7.1 and 7.2) and scenario based event trees (Figure 7.5 and 7.6). Input into these assessments was derived from the functionality functions as well as from questionnaire data, and experience gained throughout the field and laboratory experiments. These assessments can be used, by anyone, to quickly determine which laptop components have a higher risk of loss of function, under certain volcanic ash and gas conditions.

The risk tables indicate the probability of a reduction in functionality, but not the degree of reduction, of a laptop as a whole and its individual components for various ash thicknesses and grain size (Table 7.1) and various gas exposure durations (Table 7.2). Generally, the thicker the ashfall and the longer the gas exposure duration, the higher the probability of reduced laptop function.

Table 7.1: Qualitative assessment of the probability of a reduction in functionality of a laptop computer and its components under different volcanic ash conditions. Fine ash is <500 µm, coarse ash is >500 µm.

Component	**Probability of Reduction in Functionality**					
	Ash Thickness <5 mm		Ash Thickness 5-50 mm		Ash Thickness >50 mm	
	Fine	Coarse	Fine	Coarse	Fine	Coarse
Laptop	Low	Low	Medium	Low	Medium	Medium
CPU	Low	Low	Low	Low	Low	Low
CD Drive	Medium	Low	High	Low	High	Low
Hard Drive	Low	Low	Low	Low	Low	Low
Motherboard	Low	Low	Low	Low	Low	Low
Cooling Fan	Low	Low	Medium	Low	Medium	Low
Keyboard	Medium	Medium	Medium	High	High	High
Mouse Pad	Low	Low	Low	Low	Medium	Medium

Table 7.2: Qualitative assessment of the probability of a reduction in functionality of a laptop computer and its components after different volcanic gas exposure durations.

Component	**Probability of Reduction in Functionality**		
	Volcanic Gas Exposure Duration		
	<1 day	1 day-1 year	>1 year
Laptop	Low	Medium	Medium-High
CPU	Low	Low	Low
CD Drive	Low	Low	Medium
Hard Drive	Low	Low	Low
Motherboard	Low	Medium	High
Cooling Fan	Low	Medium	High
Keyboard	Low	Medium	Medium
Mouse Pad	Low	Medium	Medium

Scenario based event trees were created for both ash (Figure 7.5) and gas (Figure 7.6) related exposure, to show which hazard scenarios could lead to a reduction in laptop computer components, running from left to right. These event trees can be used by anyone in a volcanic environment to quickly assess how the environment they are in, may affect laptop computers. The functionality functions that were developed in Section 7.2 can be applied to the ashfall event tree at the node where the question, ‘are the laptops protected?’ is posed. This will then give the scenario where a reduction in functionality is possible and then the quantity of that reduction.

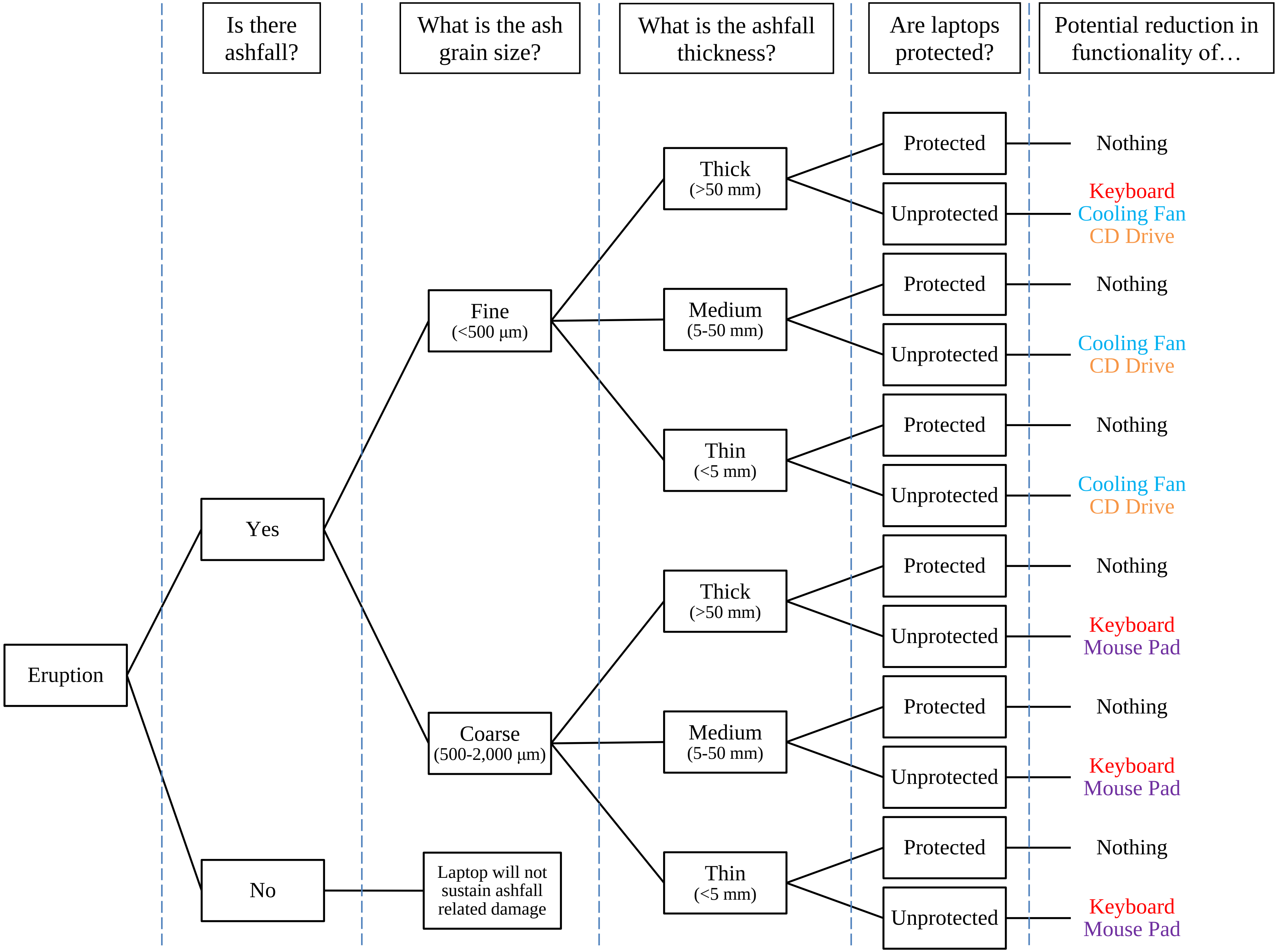

Figure 7.5: Event tree for laptop computers during volcanic ashfall. 'Protected' indicates that the laptop is fully sealed from the environment.

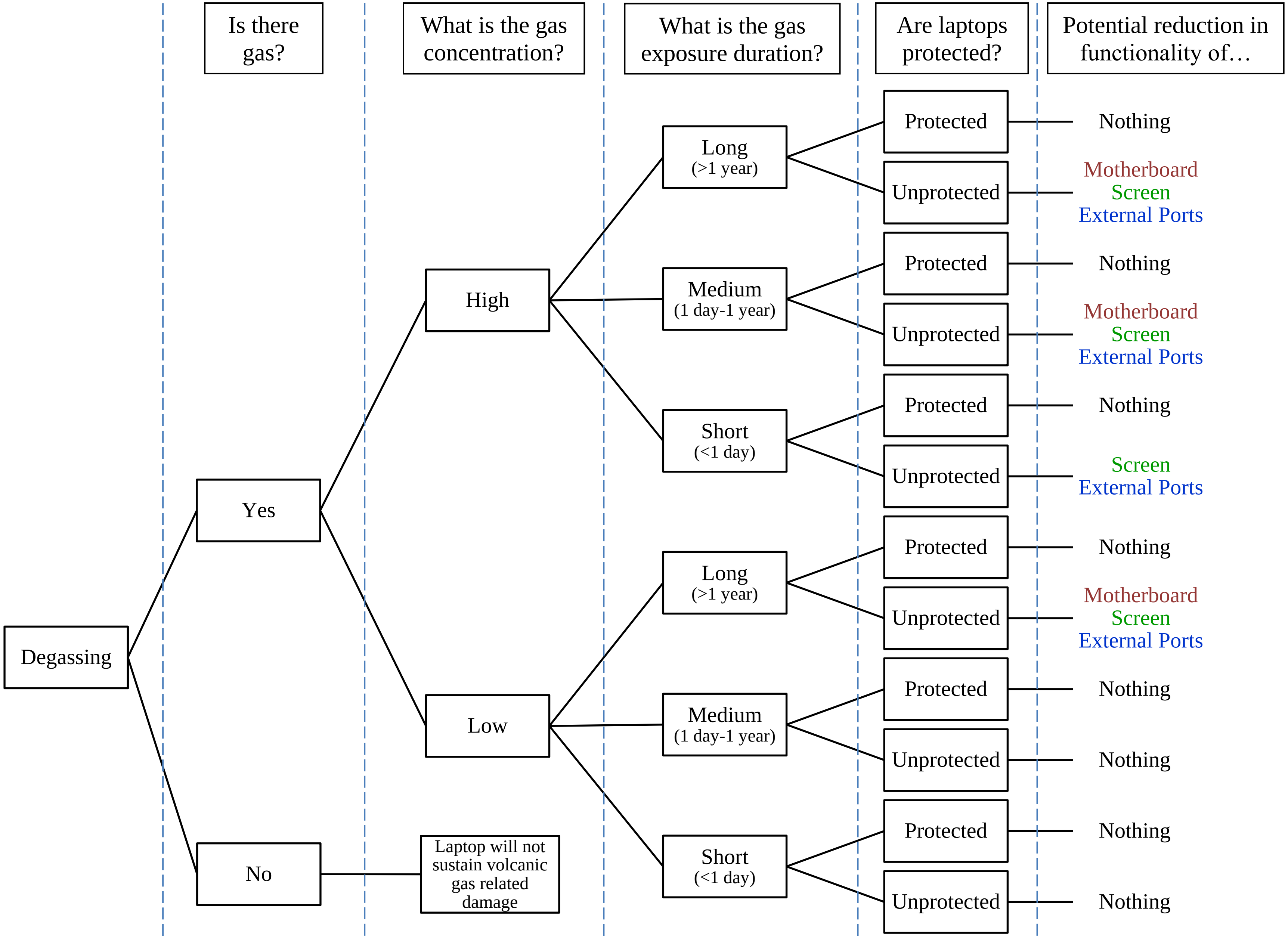

Figure 7.6: Event tree for laptop computers during exposure to volcanic gases. 'Protected' indicates that the laptop is fully sealed from the environment.

Chapter Eight – Conclusions and Recommendations

8.1. Conclusions

In this study, laptop computers were subjected to volcanic ash and gas hazards in both laboratory and field settings. It was found that laptops, overall, have a relatively low risk of damage from these hazards, however, they have a low-medium risk of loss of functionality in ash environments.

During laboratory ashfall vulnerability testing, of up to 160 hours, not one of the ten laptops used was permanently damaged by volcanic ash. There was however, a loss of functionality of up to 80% for keyboards, CD drives and cooling fans due to jamming of the components by ash. During the testing, ash settled on the keyboards causing the keys to jam, reducing overall functionality. In addition, small quantities of dry fine grained ash was able to enter laptop cases, through various ventilation holes and joints, and settle on the internal components. Because the ash contained no moisture, it did not cause any shorting of electrical components. As ash laden air was pulled though cooling fans, it caused three of them to become jammed and cease working, leading to overheating of the three laptops, which eventually resulted in shutdowns. The inside of CD drives and the CDs themselves became covered in fine grained ash, which meant that the data on the disk could no longer be read. Due to the reduced mobility of moist ash, it was not able to enter the laptop to cause short circuits or corrosion damage. Removing all traces of ash after exposure was time consuming and in some cases required dismantling of the entire laptop. The use of simple mitigation techniques such as placing the laptop inside a heavy duty plastic bag or carry bag prevented ash from entering the laptop while still maintaining full functionality. This technique, along with regular cleaning of laptops will allow them to continue to operate in the field over long timeframes.

Short term field based volcanic gas vulnerability testing on White Island, showed that laptops sustained only minor corrosion damage to non-essential metal components. The small amount of damage sustained did not affect laptop functionality and the laptops used for these tests still operate normally 18 months after exposure. However, nine unprotected PCBs sustained significant corrosion damage after being exposed to volcanic gases for 26 hours, and as a result lost all functionality. No long term vulnerability experiments were undertaken due to time constraints, but it is likely that increased exposure will result in more corrosion damage. This is supported by some questionnaire responses from Rotorua businesses who indicate that they have had corrosion related damage to computers over 6 months-5 years. The same simple mitigation techniques that are recommended for ash hazards can be applied to gas related hazards. Placing laptops in sealed plastic bags will reduce their exposure to volcanic gas to zero, and will allow them to operate over long timeframes while maintaining full functionality and sustaining no damage.

8.2. Recommendations

The main recommendation for the volcanology and critical infrastructure communities is to totally isolate laptop computers from volcanic ash and gas hazards to reduce risk of failure to zero. Where this is not possible, the application of the mitigation techniques for laptop protection outlined in Section 5.5 will minimise the risk to laptop computers in volcanic environments. If volcanic ash and/or gas is deposited on or enters a laptop it is recommended that it stop being used and is taken out of the hazard zone immediately and then cleaned thoroughly.

It is also recommended that volcanic observatories and research groups undertake their own field based research into volcanic impacts on electronic equipment. This is because equipment damage and functionality reduction is dependent on the conditions at the time of exposure, which is very difficult to replicate in the laboratory. This continued international research will help further develop the understanding of how electronic equipment will function in volcanic environments.

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Appendix C – Volcanic Ash Leachate Concentrations

Table C.1: Comparison of volcanic ash leachates from different volcanic eruptions. All concentrations are in mg/L.

Element	Mt St Helens 1980[1]	Mt St Helens 1980[2]	Fuego Ash 1973 & 1974[3]	Pacaya Ash 1974[3]	Santiaguito Ash 1967 & 1975[3]	Ruapehu 1995-96[4]	Popocatepetl 1994-1996[5]	Popocatepetl 1996[6]	Popocatepetl 1997[6]	Popocatepetl 1998[6]
Al	-	0.32	1.3	3.20	1.30	10.3	-	-	-	-
B	-	0.04	0.02	0.02	0.27	-	-	-	-	-
Br	-	-	-	-	-	0.30	-	-	-	-
Ca	-	29.6	100.0	49.0	150.0	211.6	88.9	-	-	-
Cl	205.9	25.4	31.0	51.0	110.0	39.6	16.3	4.07	4.55	11.1
F	1.85	0.64	5.30	7.20	3.60	3.08	2.50	1.01	4.66	2.54
Fe	0.10	0.33	0.52	0.70	0.39	1.56	-	-	-	-
Li	0.05	0.02	0.01	0.00	0.10	0.10	-	-	-	-
K	-	4.31	-	-	-	4.01	7.90	-	-	-
Mg	11.9	3.28	5.50	4.90	24.0	29.8	5.96	-	-	-
SiO_2	10.03	-	-	-	-	-	-	-	-	-
SO_4^{2-}	259.1	78.3	-	-	-	702.5	253.2	16.3	20.5	87.3

[1] Smith *et al.* (1983); [2] Fruchter *et al.* (1980); [3] Smith *et al.* (1982); [4] Christenson (2000); [5] Armienta *et al.* (1998); [6] Armienta *et al.* (2002).

Appendix D – Laptop Computer Specifications

Table D.1: Laptop computer specifications. M: Mobile; MHz: Megahertz; MB: Megabyte; GB: Gigabyte.

Computer Number	**Computer Name**	**CPU Type**	**CPU Speed** (MHz)	**RAM** (MB)	**Hard Drive Size** (GB)	**CD, Floppy Drive**	**Windows Version**	**Tests**
1	Acer Extensa	Intel Pentium		80	3	Yes, No	2000	Ash
2	Acer Aspire 2010	Intel Pentium M	1,500	512	40	Yes, No	XP Home	Gas
3	Toshiba	Intel Celeron M	2,200	256	28	Yes, No	XP Home	Ash
4	PC Company	Intel Pentium		256	28	Yes, Yes	XP Home	Gas
5	HP Pavilion ZE4300	Intel Celeron M	2,200	512	28	Yes, Yes	XP Home	Ash
7	Dell Inspiron 1150	Intel Celeron	2,400	1024	15	Yes, No	XP Home	Gas & Ash
9	Toshiba TE2000	Intel Pentium III M	1,133	256	9	Yes, No	XP Home	Ash
10	Toshiba TE2000	Intel Pentium III M	1,133	256	9	Yes, No	XP Home	Ash
11	Dell Latitude	Intel Pentium		96	4	Yes, No	2000	Ash
12	Dell Latitude	Intel Pentium		96	4	Yes, No	2000	Ash
17	Compaq Evo N160	Intel Pentium III M	1,000	640	37	Yes, No	XP Pro	Ash
18	Compaq Evo N160	Intel Pentium III M	1,000	640	37	Yes, No	XP Pro	Ash

Appendix E – How a Laptop Computer and its Components Work

Laptop computers operate in the same way as desktop computers, with the main difference being how the components fit together. Laptops are designed to be portable and because of this, all of the components fit together in one compact unit. Due to this compact design, components are required to be small, conserve power and produce less heat than desktop components.

The following is a brief description of the main components within a laptop computer.

Motherboard:
The motherboard is the central printed circuit board in all computers and holds many of the crucial components (CPU, graphics, RAM) of the system (Figure E.1). It also provides electrical connections to all components so they can communicate. The motherboard includes slots for connecting RAM and expansion cards (e.g. graphics cards) and has ports for connecting external devices (e.g. USB flash drives). Due to the compact design of laptop computers the motherboards are significantly smaller than desktop motherboards, and typically do not include the large expansion card slots.

Central Processing Unit (CPU):
The CPU is a single chip microprocessor comprised of billions of transistors that carry out the instructions of a computer programme. Laptop CPUs are the same dimensions as desktop CPUs, however they operate at a lower speed and voltage to reduce heat output and power consumption. Heat is removed through a heat sink and cooling fan (Figure E.2).

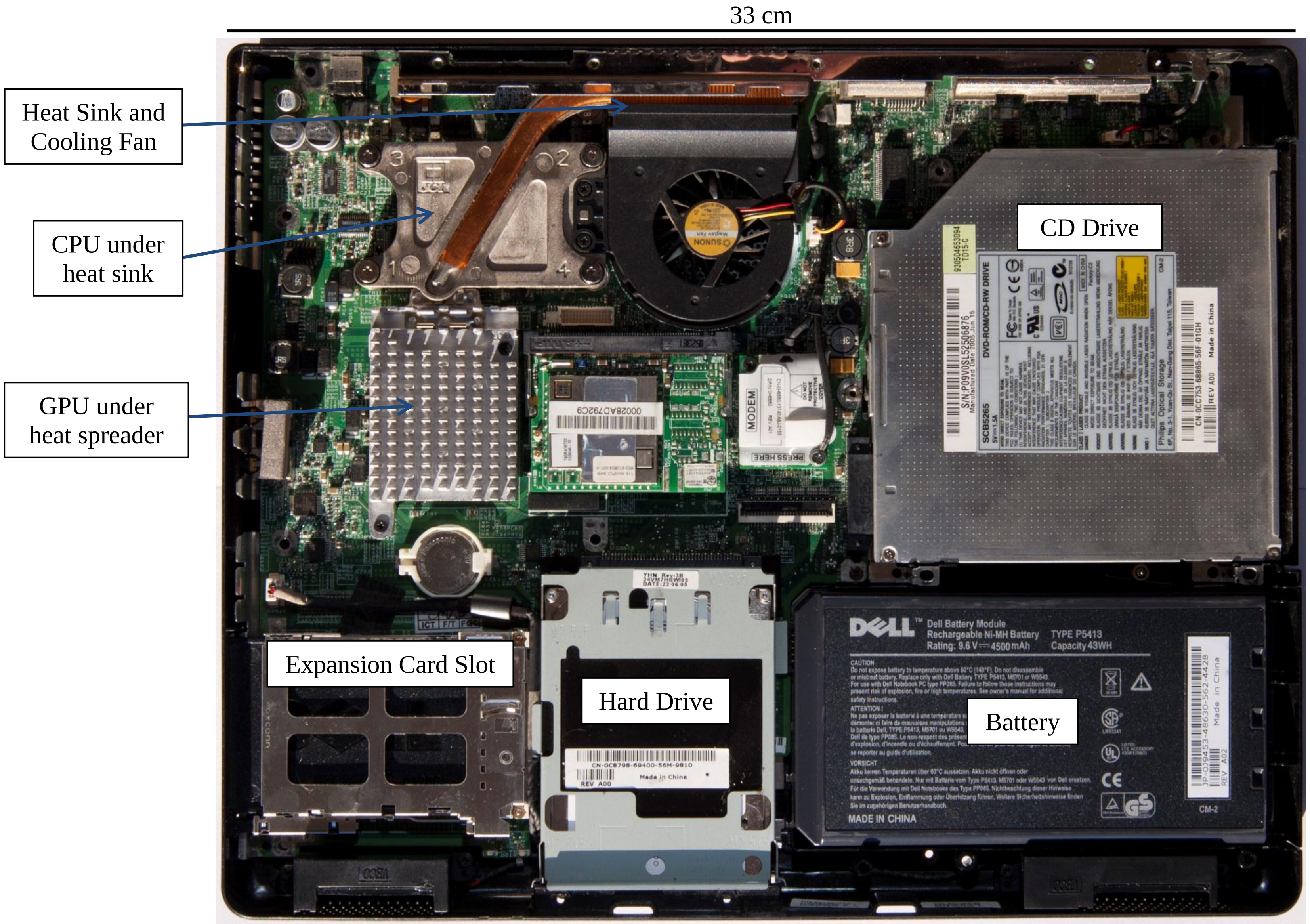
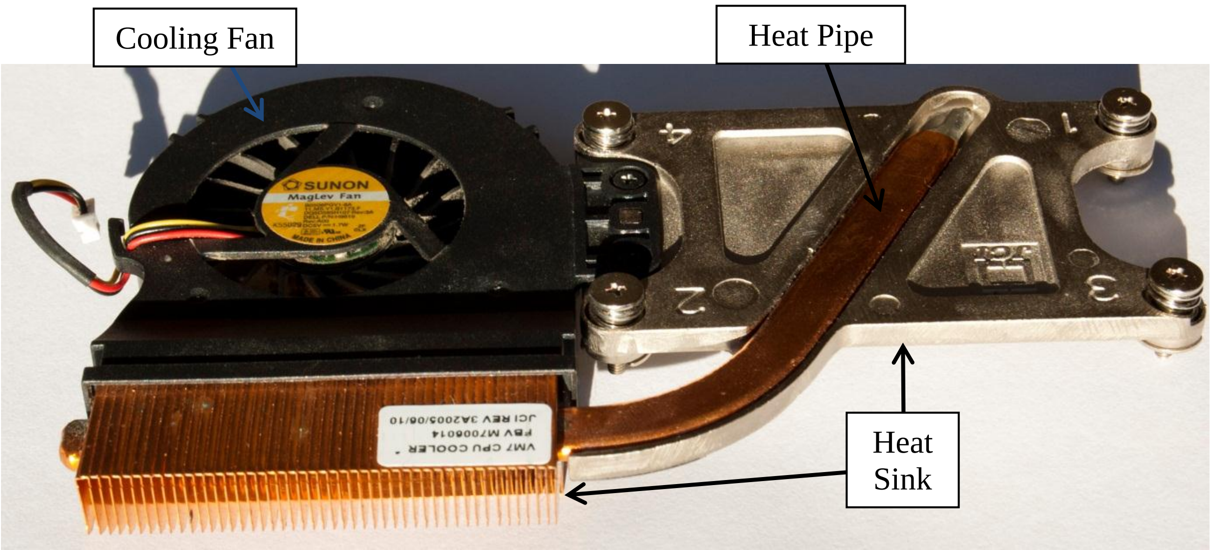


Figure E.1: Photograph of the inside of a laptop computer showing the motherboard and the components connected to it. Front of laptop is at bottom.



14 cm

Figure E.2: Typical laptop heat sink and cooling fan. Heat is transferred along the heat pipe to the fins on the left, where the fan blows air through the fins removing the heat from the laptop.

Random Access Memory (RAM):

Random access memory is a form of computer data storage. RAM modules are integrated circuits containing transistors and capacitors similar to microprocessors (Figure E.3). RAM is available to all components within the computer for short term data storage, and unlike a hard drive, no data can be permanently stored on RAM modules. These modules are usually located on the underside on laptop motherboard, behind removable covers.

7 cm

Figure E.3: Laptop RAM module.

Graphics Processing Unit (GPU):

The GPU is a microprocessor like the CPU and handles the calculations required for 3D graphics rendering. Unlike desktop GPUs which are built onto large expansion cards, laptop GPUs are attached directly to the motherboard as a single chip. Like CPUs, GPUs produce a lot of heat and require heat spreaders to remove it. These usually consist of a plate of metal with a large surface area in direct contact with the chip.

Hard Drive:

A hard drive is a permanent data storage device common in all computers (Figure E.4). They store data magnetically, on rotating rigid platters. Data can be read and written through the use of a read/write head which floats on a film of air above the platters. In order to keep the read/write head operating at the correct height, the air pressure must equalise through the protective casing. This is achieved through a breather hole ~0.5 mm in diameter. This hole has a 0.3 μm aperture filter on the inside preventing particles getting inside the enclosure. Laptop hard drives are smaller than desktop hard drives and spin a lower speed, to reduce power consumption and heat output.

Compact Disk (CD) Drives:

CD drives use laser light to read and write data to or from an optical disk (Figure E.5). The most important part is the laser and lens, which focuses the laser beam, and photodiodes, which detects the reflected light turning it into electrical signals. There are two motors used in CD drive, one for spinning the disk the other for moving the laser along the disk diameter.

External Connectors:

External connectors are attached to the motherboard and are accessible from the exterior of the laptops case. These include USB, screen, audio and network ports which allow users to connect additional devices to their laptop.

Battery:

Laptops are designed to be portable, therefore they require a battery. Laptops use lithium-ion batteries as they are lightweight, have long life spans and do not suffer from memory effect. Battery life depends on how the computer is being used at the time and how old the battery is.

Keyboard:

Laptop keyboards are usually smaller than desktop keyboards and do not have a number pad. The keys are also smaller and have a lower profile in order to save space.

Screen:

Laptop screens are usually liquid crystal displays (LCD), although some newer model use light emitting diode (LED) technology. Screens are usually larger than 15” and once closed over the keyboard, provide a protective case for the laptop.

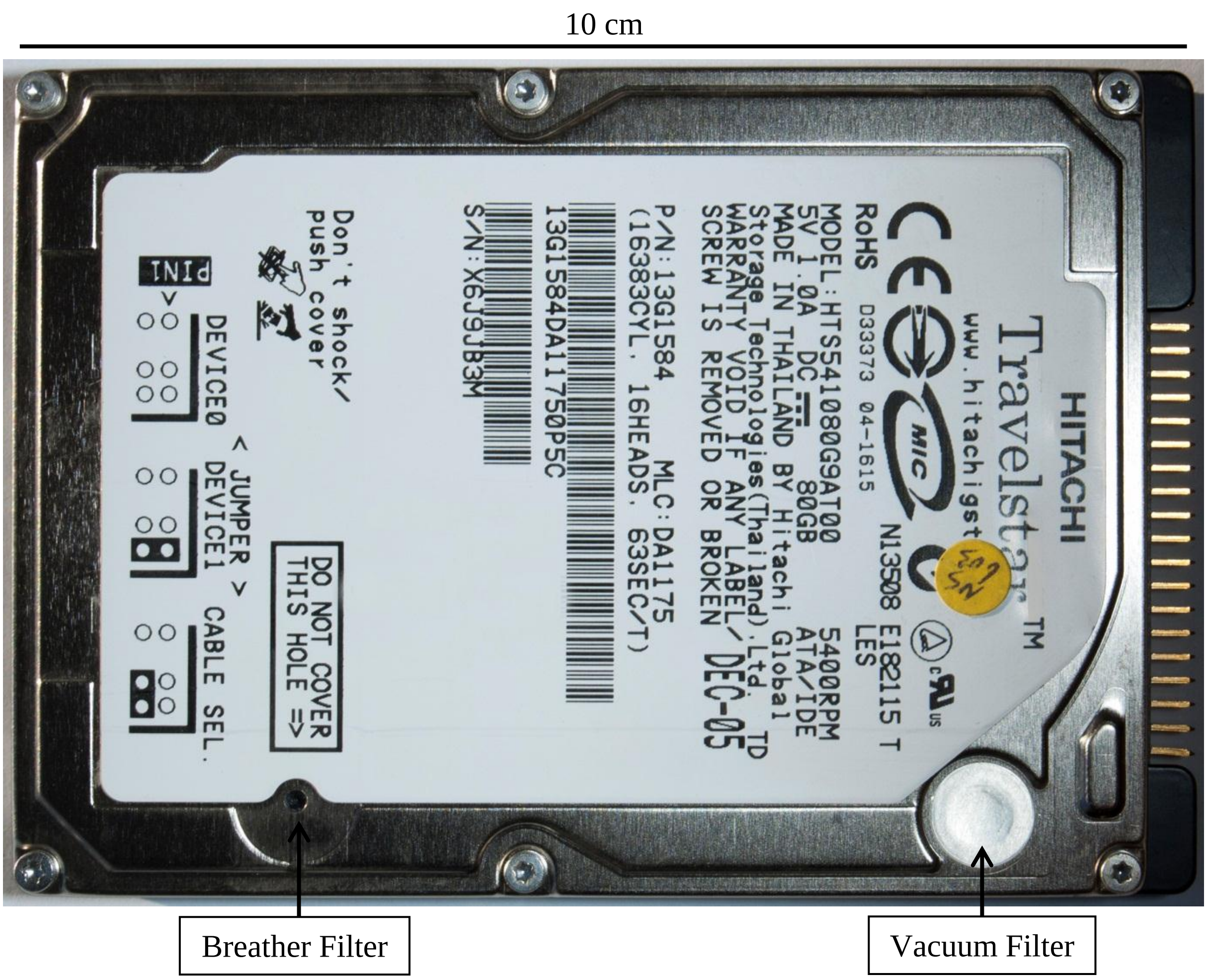


Figure E.4: Laptop hard drive.

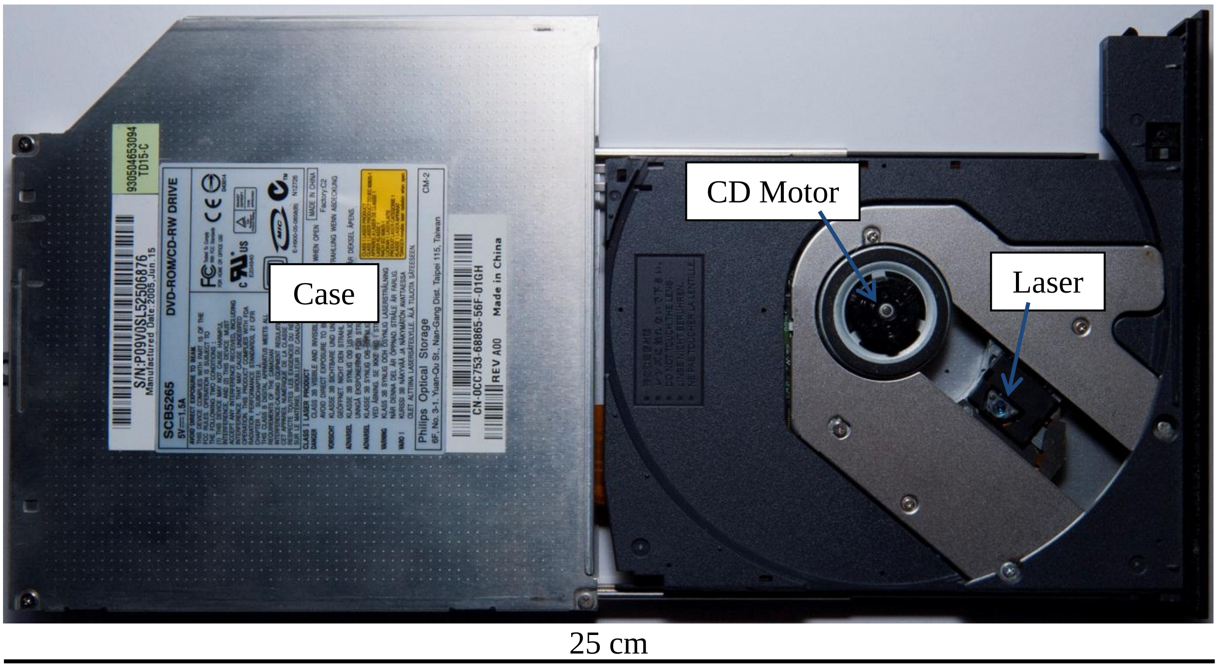


Figure E.5: Laptop CD drive.

Appendix F – Laptop Computer Performance

Figures F.1-F.8 and F.15-F.17 show laptop performance during and prior to ash and gas vulnerability tests, respectively. The number of calculations is a proxy for laptop performance. If the number of calculations increases or decreases in gradient, away from the linear trend, this indicates that the laptop's performing is increasing or decreasing, respectively.

Figures F.9-F.14 and F.18-F.19 show in average internal temperature of the laptops prior to and during ash and gas vulnerability tests, respectively.

F.1. Laptop Computer Performance During Ash Exposure

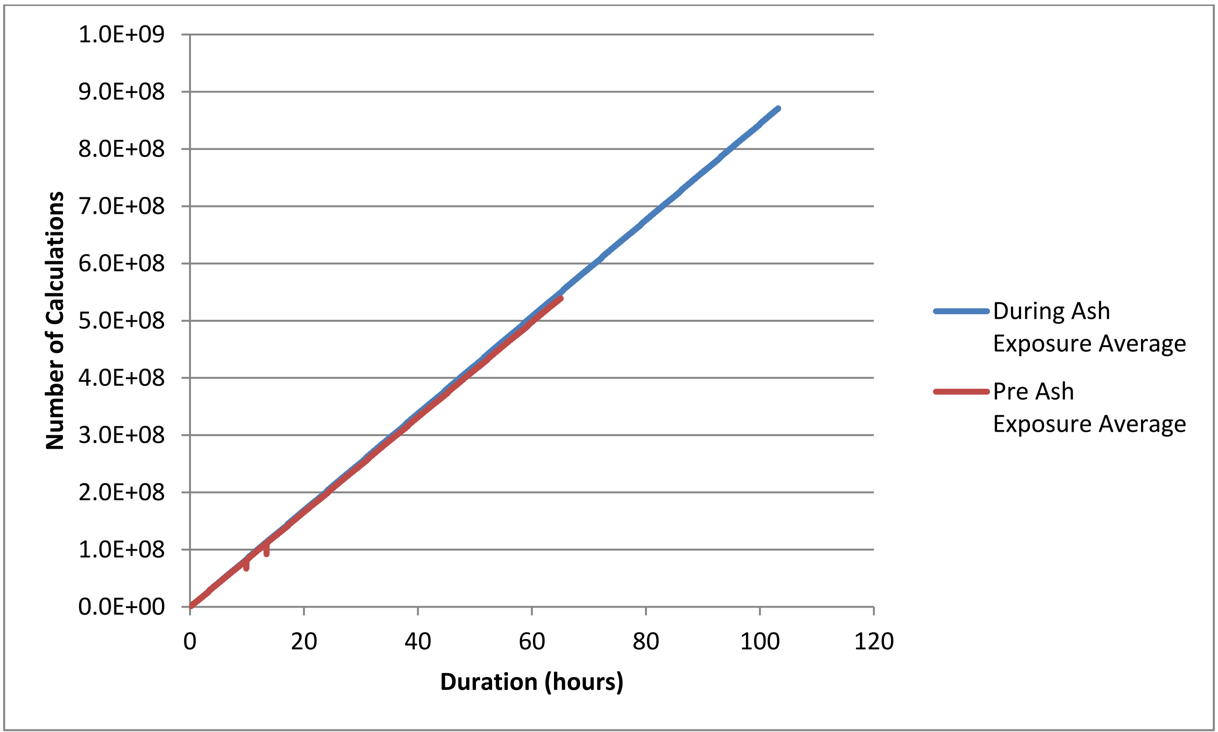


Figure F.1: Performance of Laptop 1 prior to and during ash vulnerability testing. Performance did not change.

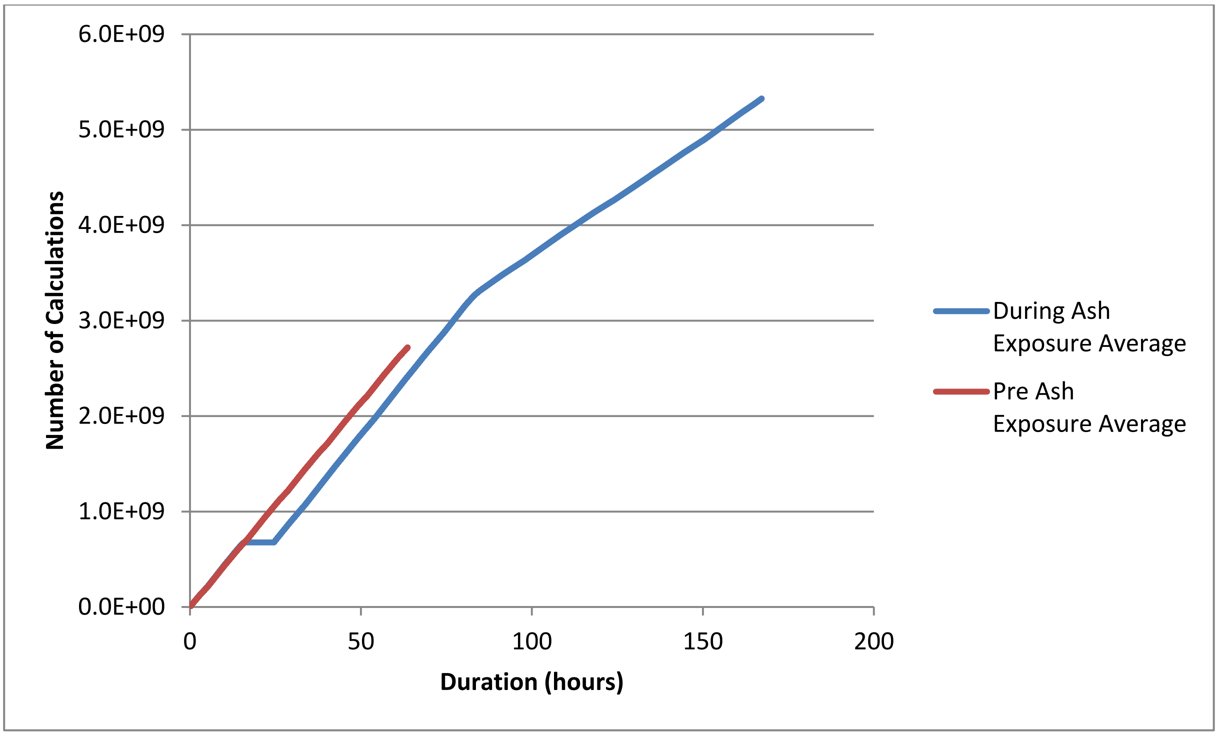


Figure F.2: Performance of Laptop 3 prior to and during ash vulnerability testing. This laptop restarted after ~25 hours of testing indicated by horizontal trend line. Performance of the laptop did decrease after ~80 hours of testing.

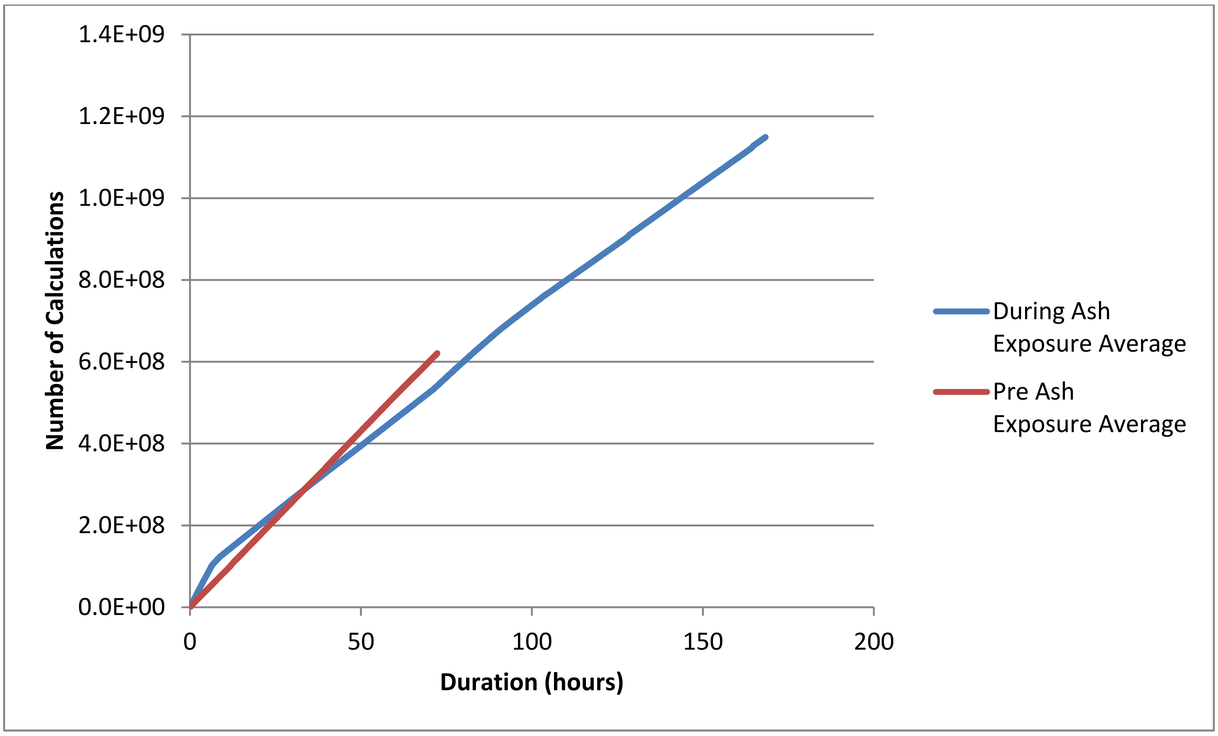


Figure F.3: Performance of Laptop 9 prior to and during ash vulnerability testing. Performance varied slightly during the ash vulnerability test.

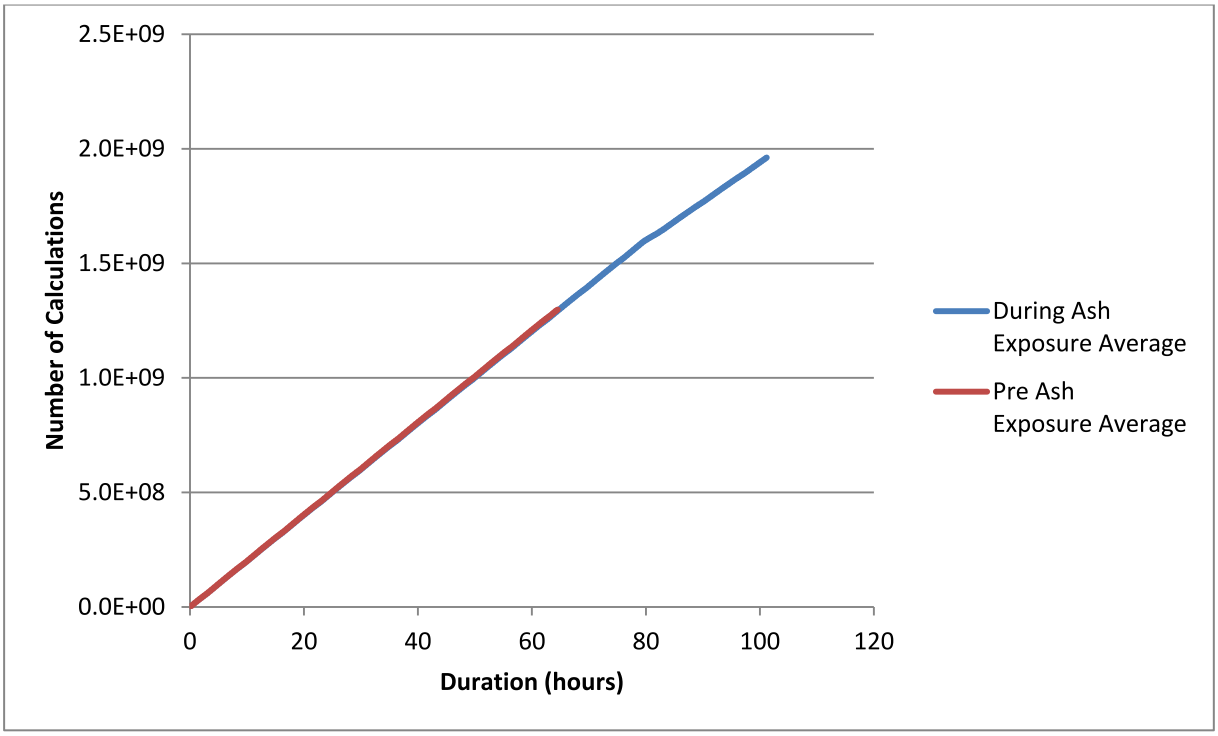


Figure F.4: Performance of Laptop 10 prior to and during ash vulnerability testing. Performance decreased slightly after ~80 hours of testing.

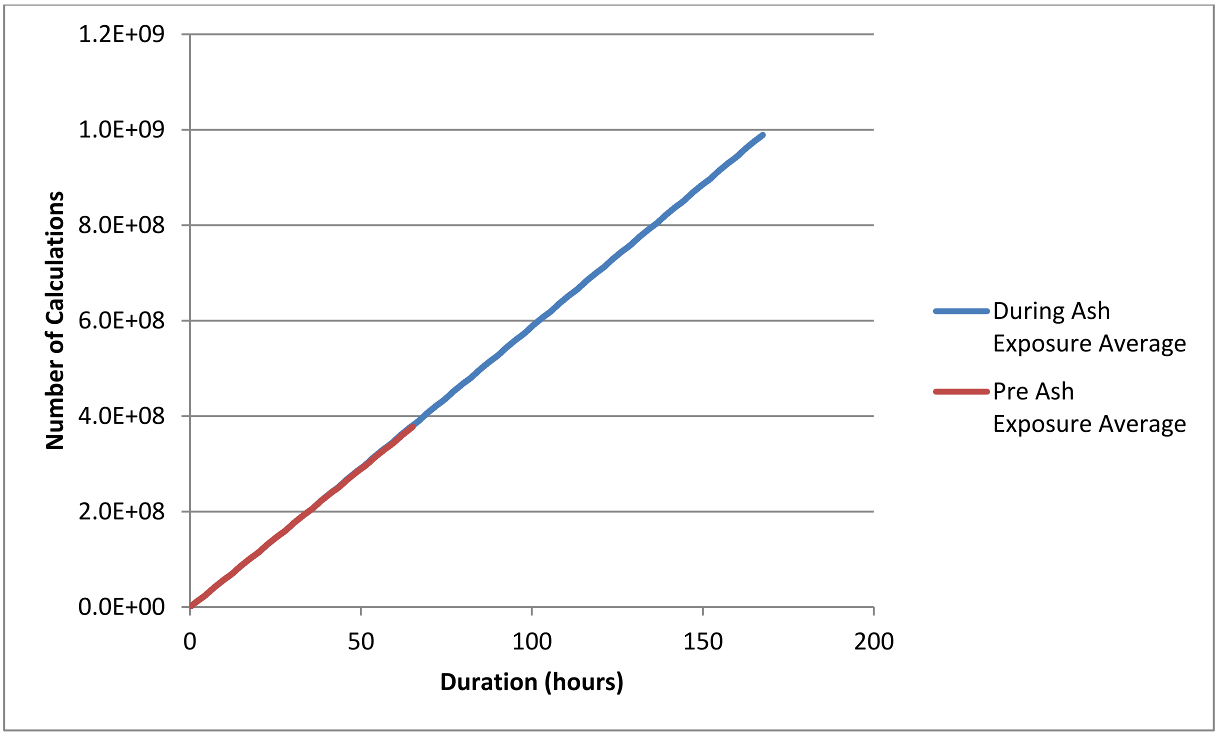


Figure F.5: Performance of Laptop 11 prior to and during ash vulnerability testing. Performance did not change.

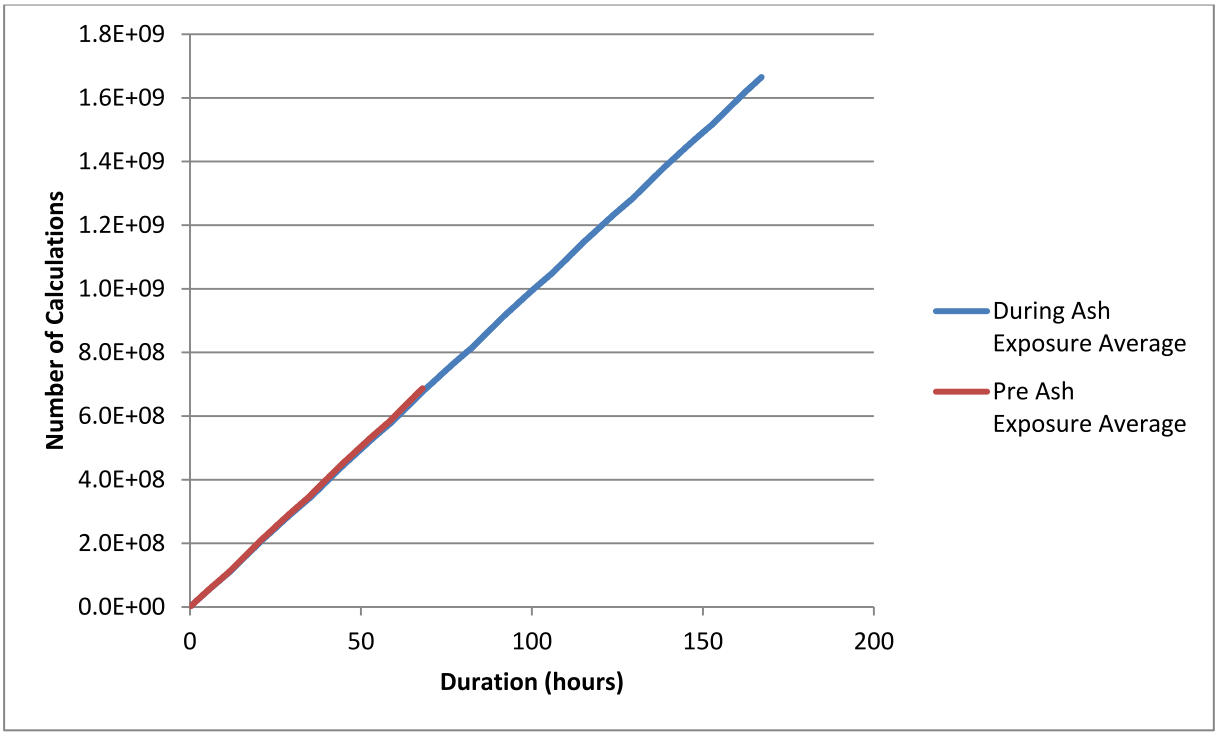


Figure F.6: Performance of Laptop 12 prior to and during ash vulnerability testing. Performance did not change.

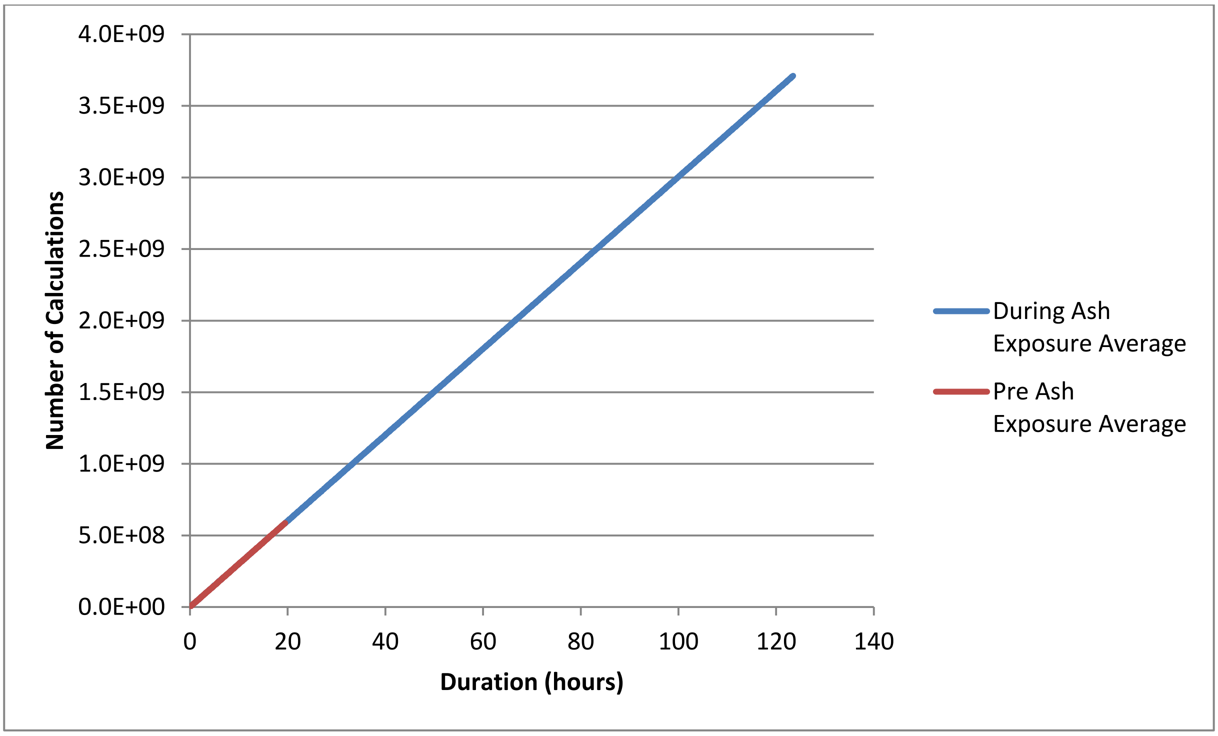


Figure F.7: Performance of Laptop 17 prior to and during ash vulnerability testing. Performance did not change.

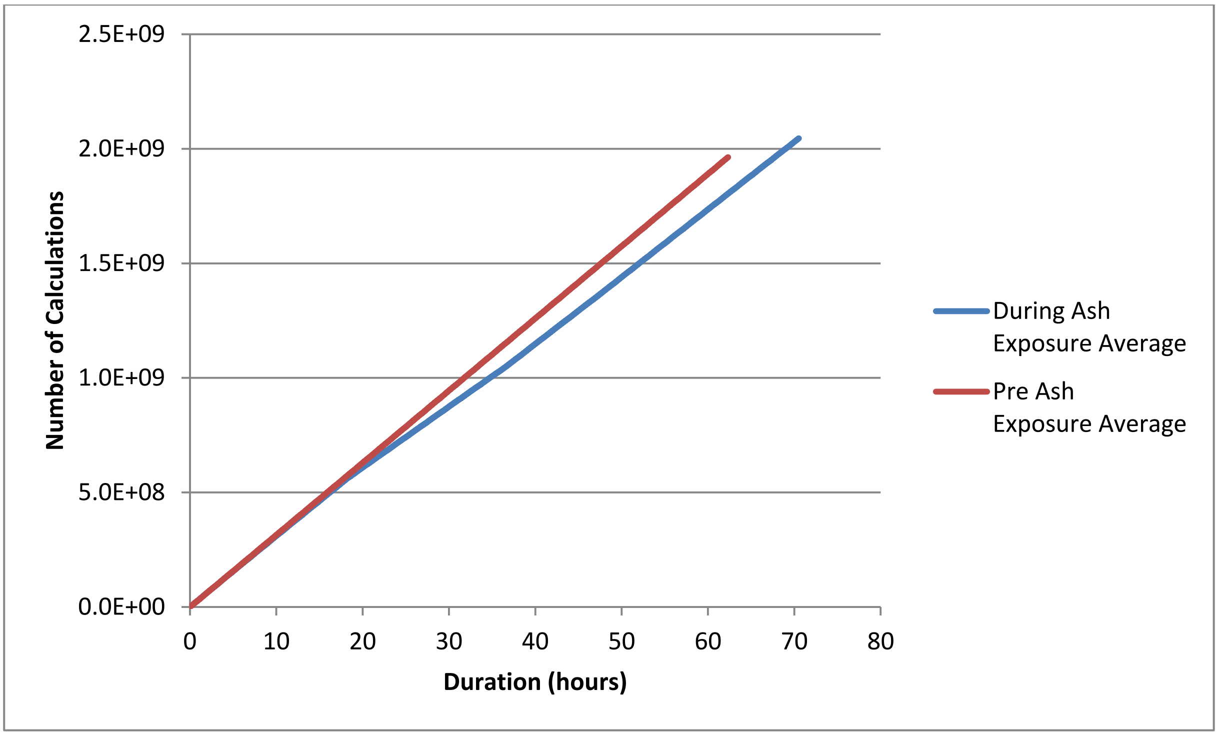


Figure F.8: Performance of Laptop 18 prior to and during ash vulnerability testing. Performance decreased slightly.

F.2. Laptop Computer Operating Temperatures During Ash Exposure

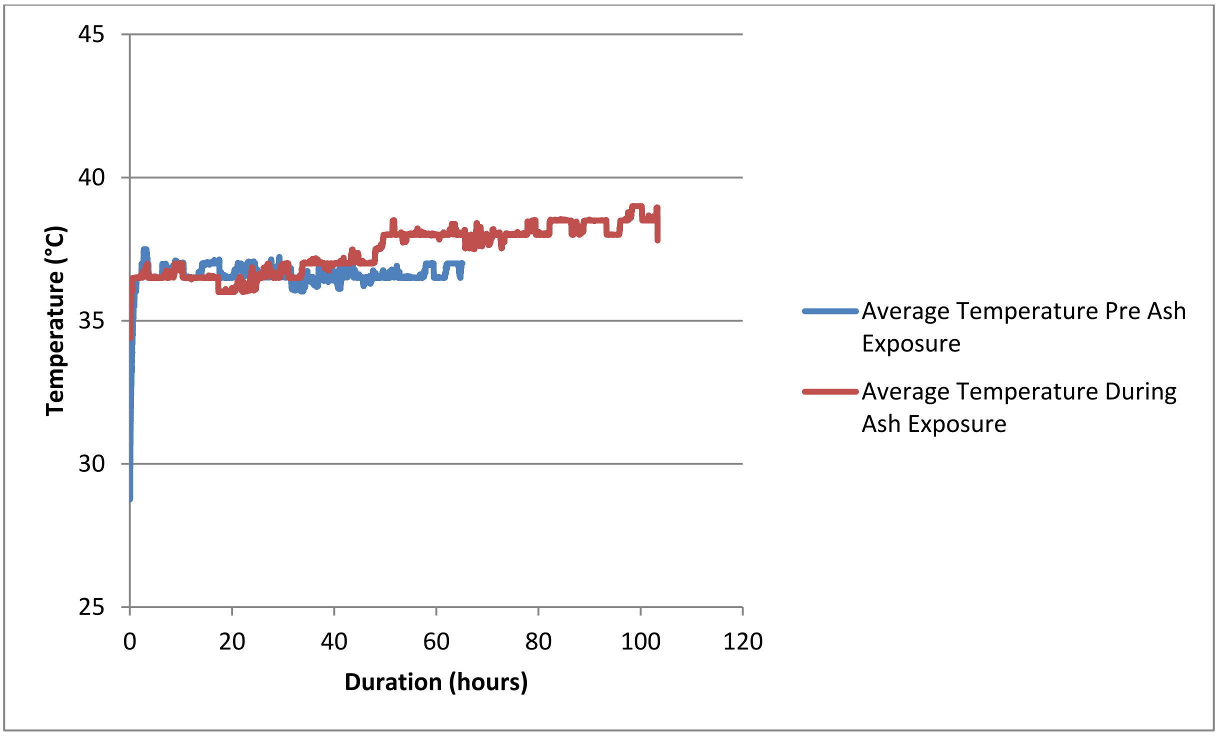


Figure F.9: Internal temperature of laptop 1 prior to and during ash vulnerability testing.

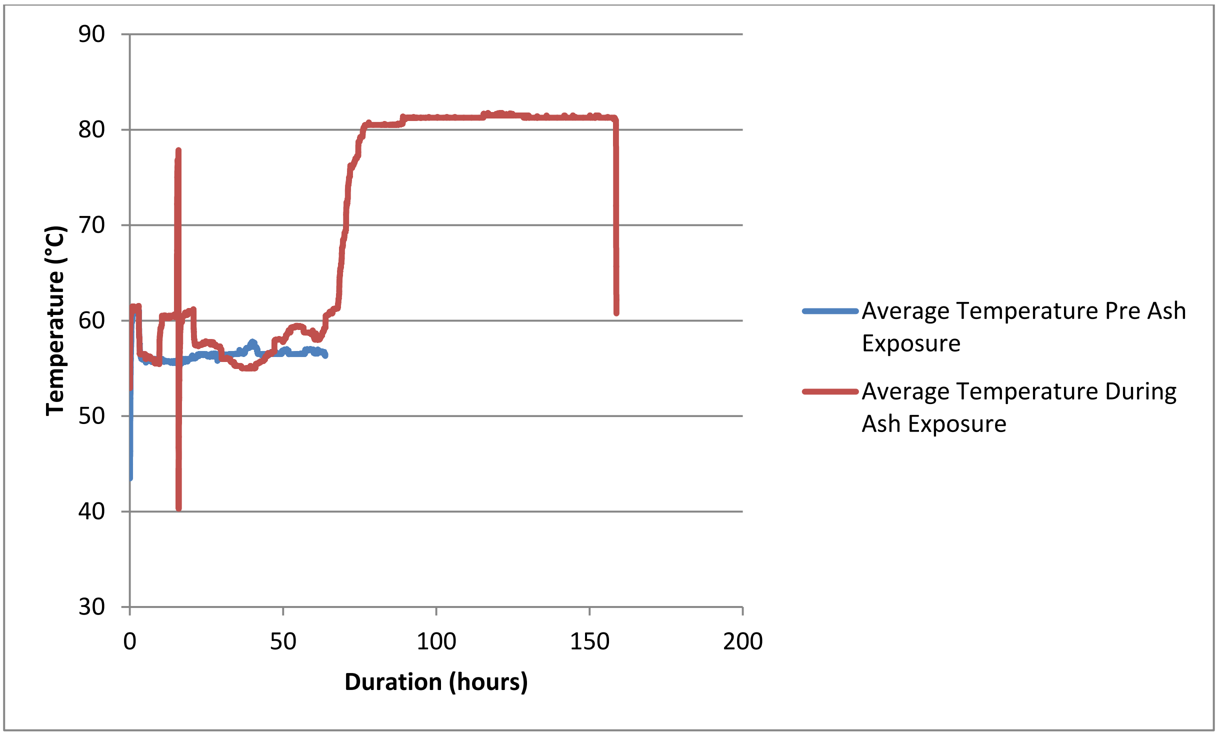


Figure F.10: Internal temperature of laptop 3 prior to and during ash vulnerability testing. This laptop overheated and shutdown.

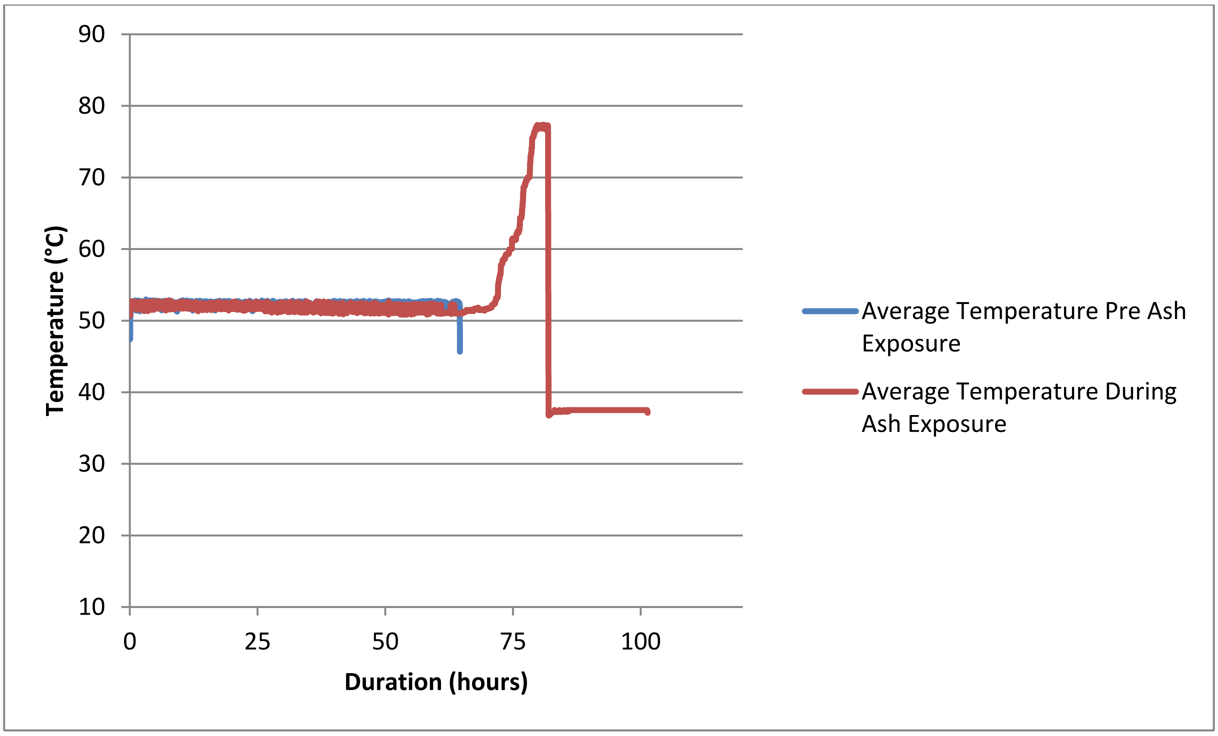


Figure F.11: Internal temperature of laptop 10 prior to and during ash vulnerability testing. This laptop overheated and restarted.

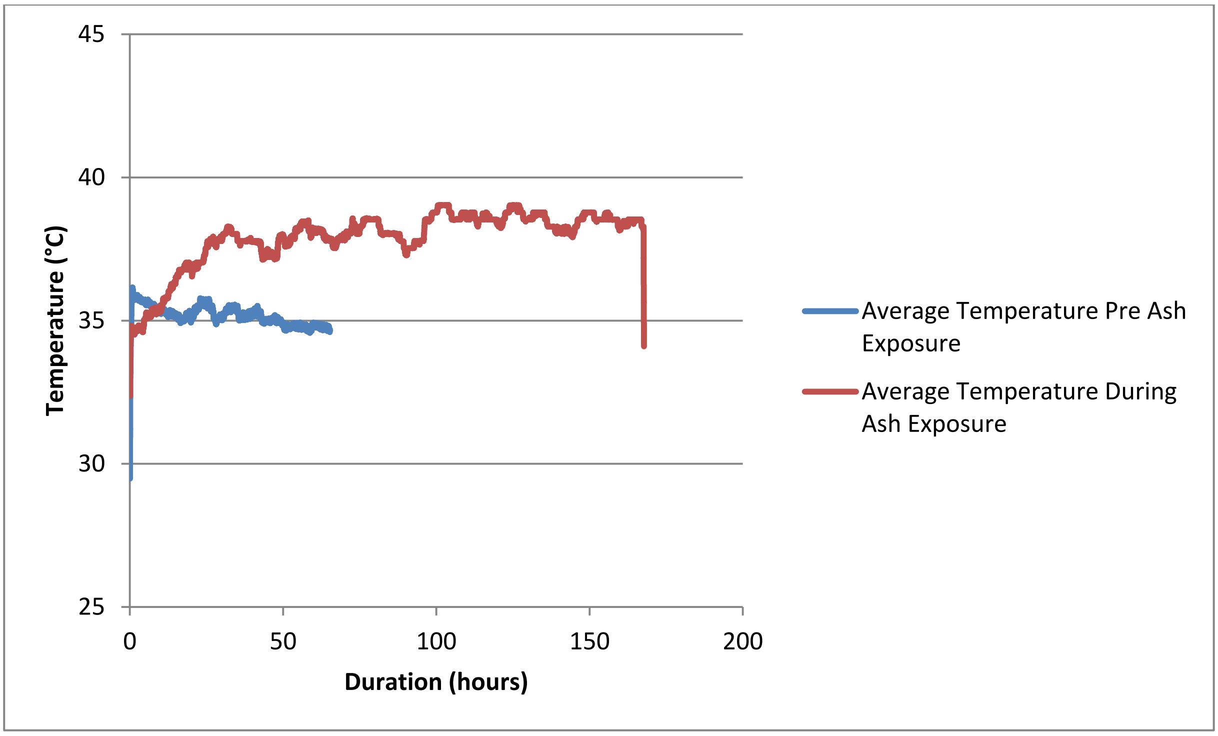


Figure F.12: Internal temperature of laptop 11 prior to and during ash vulnerability testing.

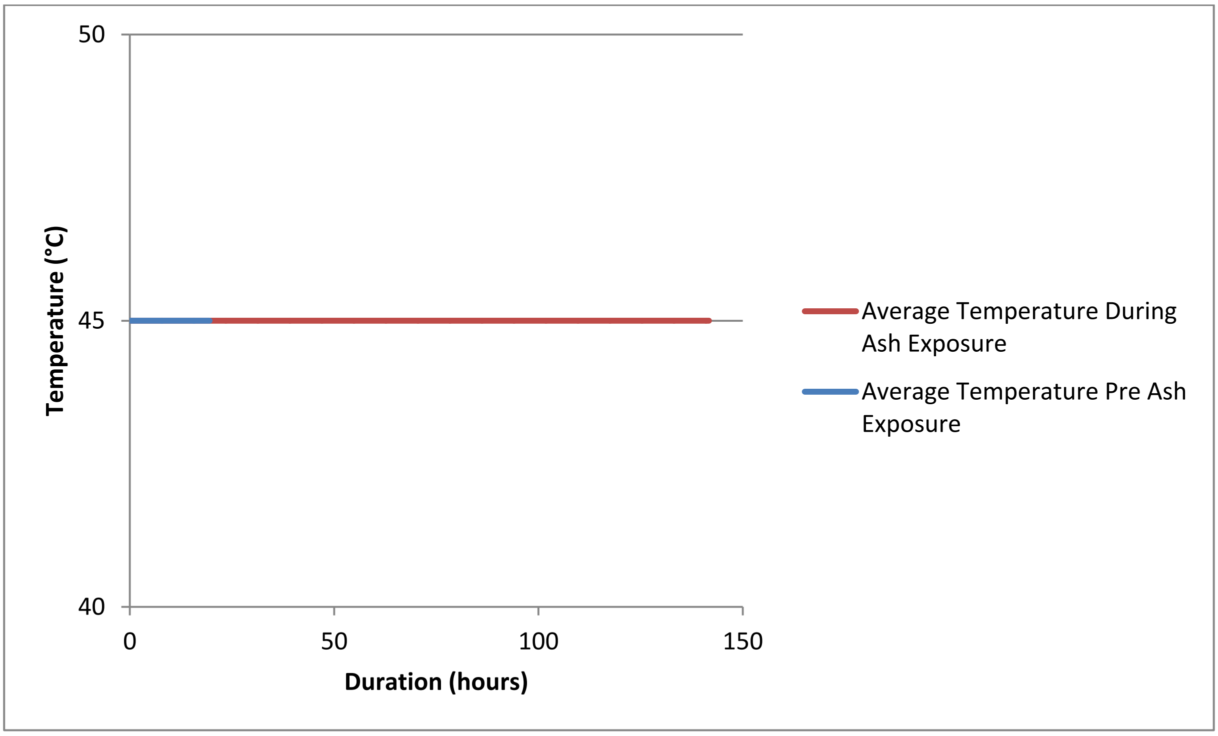


Figure F.13: Internal temperature of laptop 17 prior to and during ash vulnerability testing.

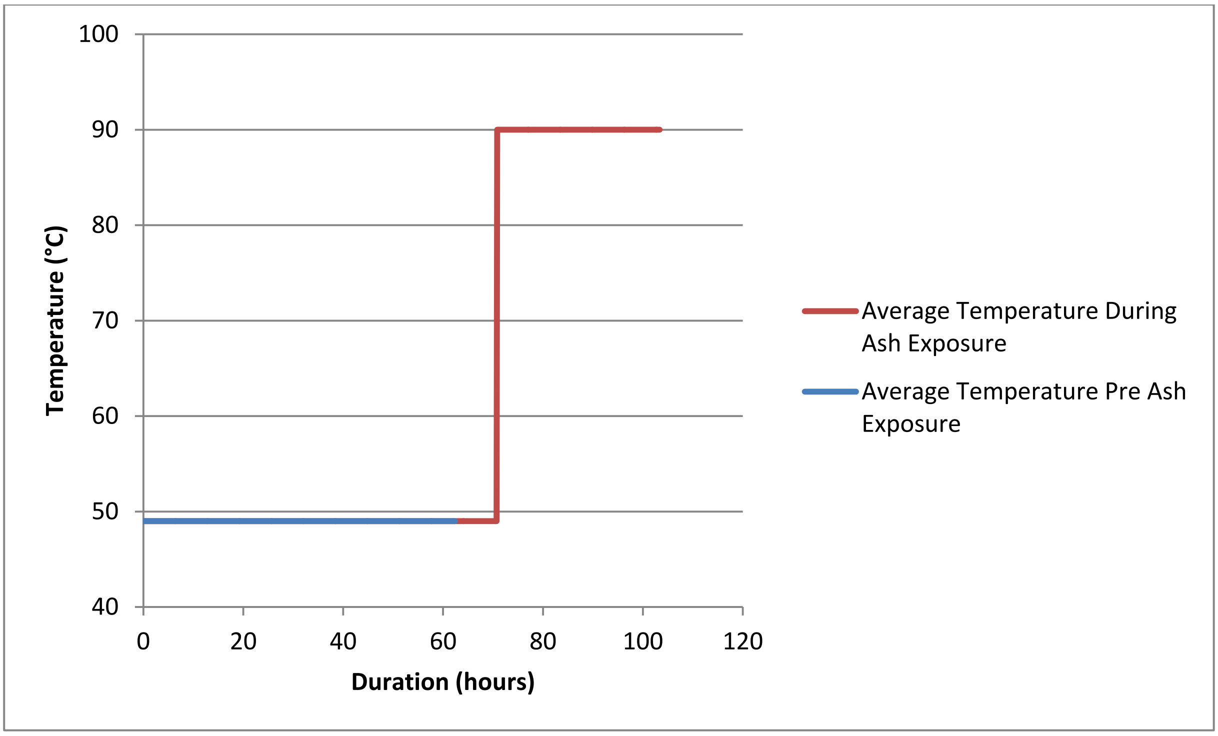


Figure F.14: Internal temperature of laptop 18 prior to and during ash vulnerability testing. This laptop overheated and shutdown.

F.3. Laptop Computer Performance During Gas Exposure

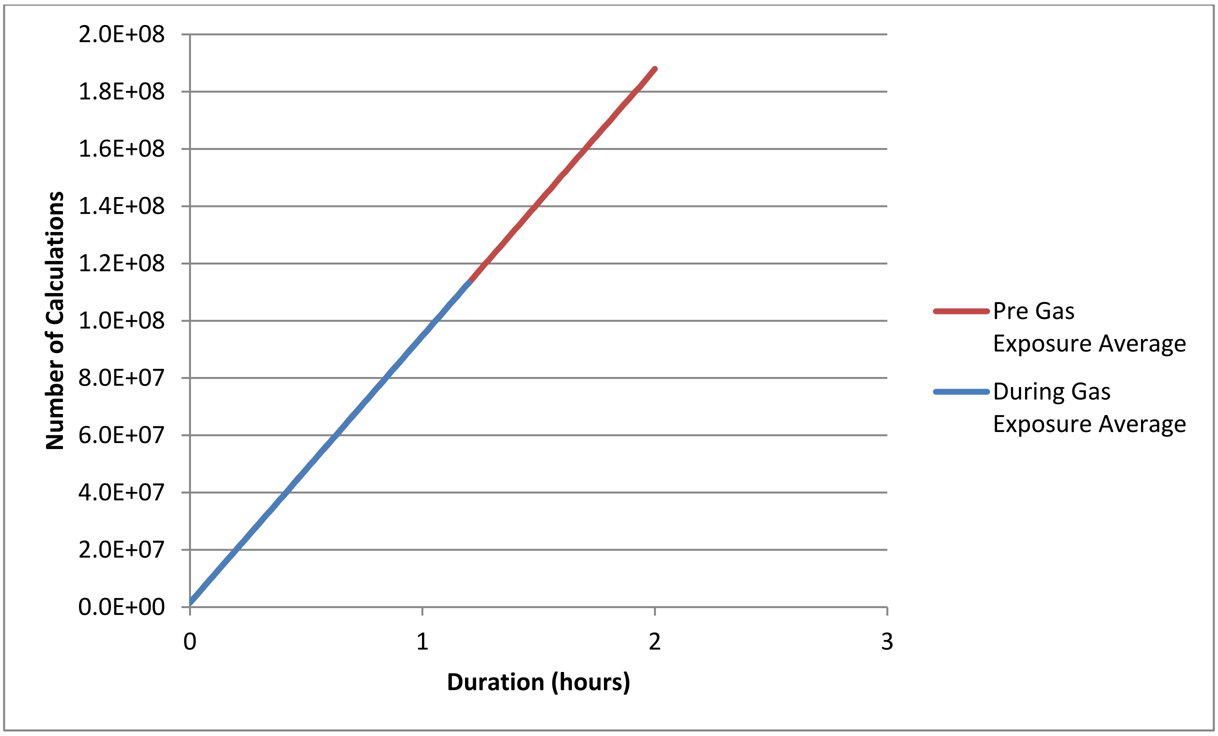


Figure F.15: Performance of Laptop 2 prior to and during gas vulnerability testing.

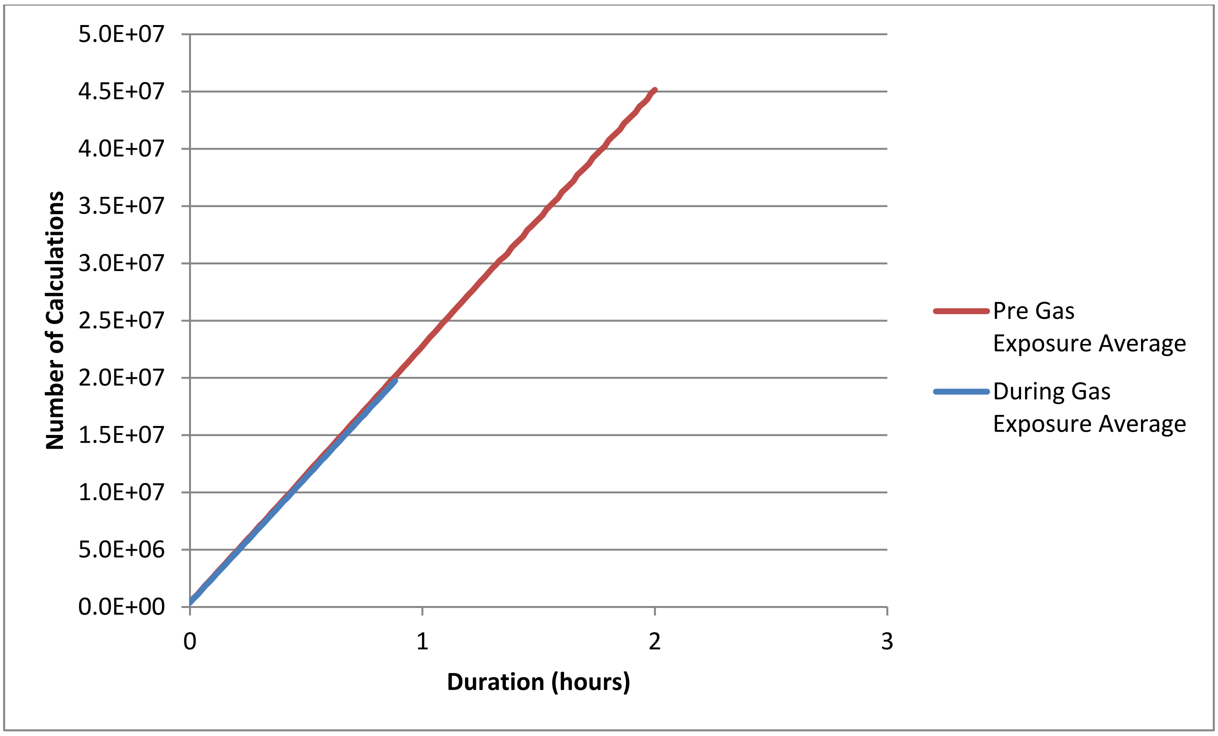


Figure F.16: Performance of Laptop 4 prior to and during gas vulnerability testing.

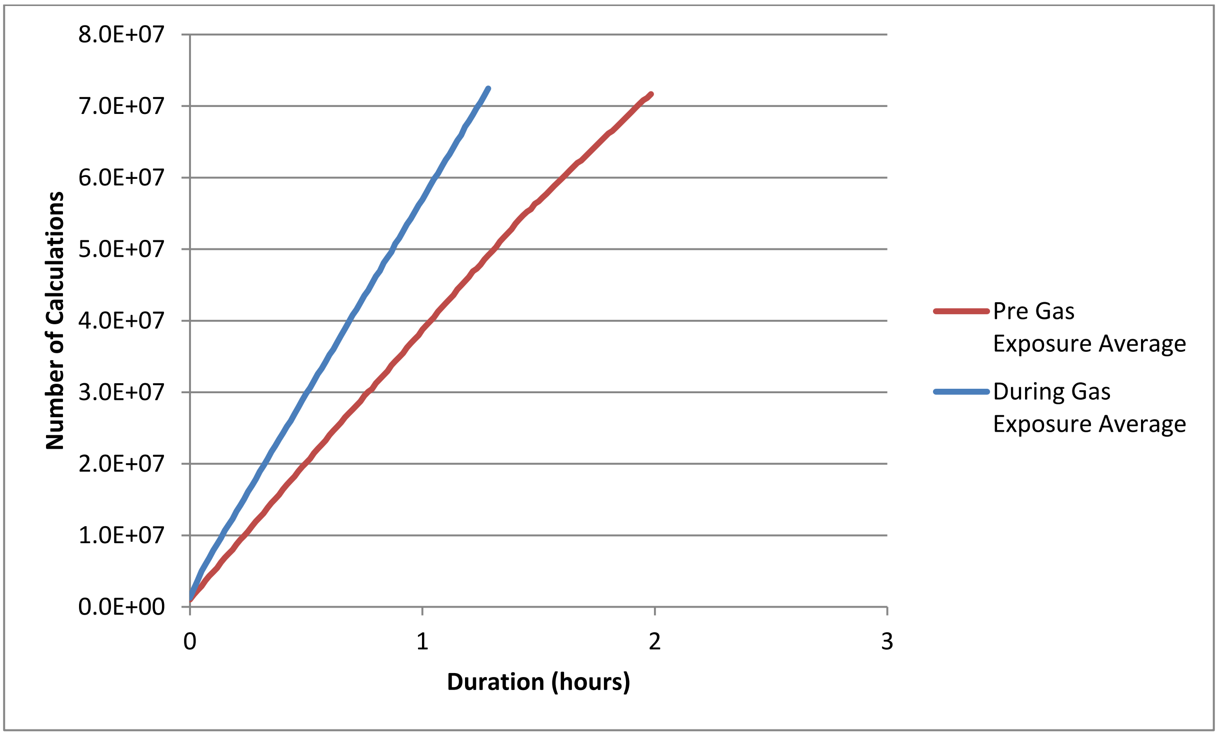


Figure F.17: Performance of Laptop 7 prior to and during gas vulnerability testing. Performance increased during gas vulnerability test.

F.4. Laptop Computer Operating Temperatures During Gas Exposure

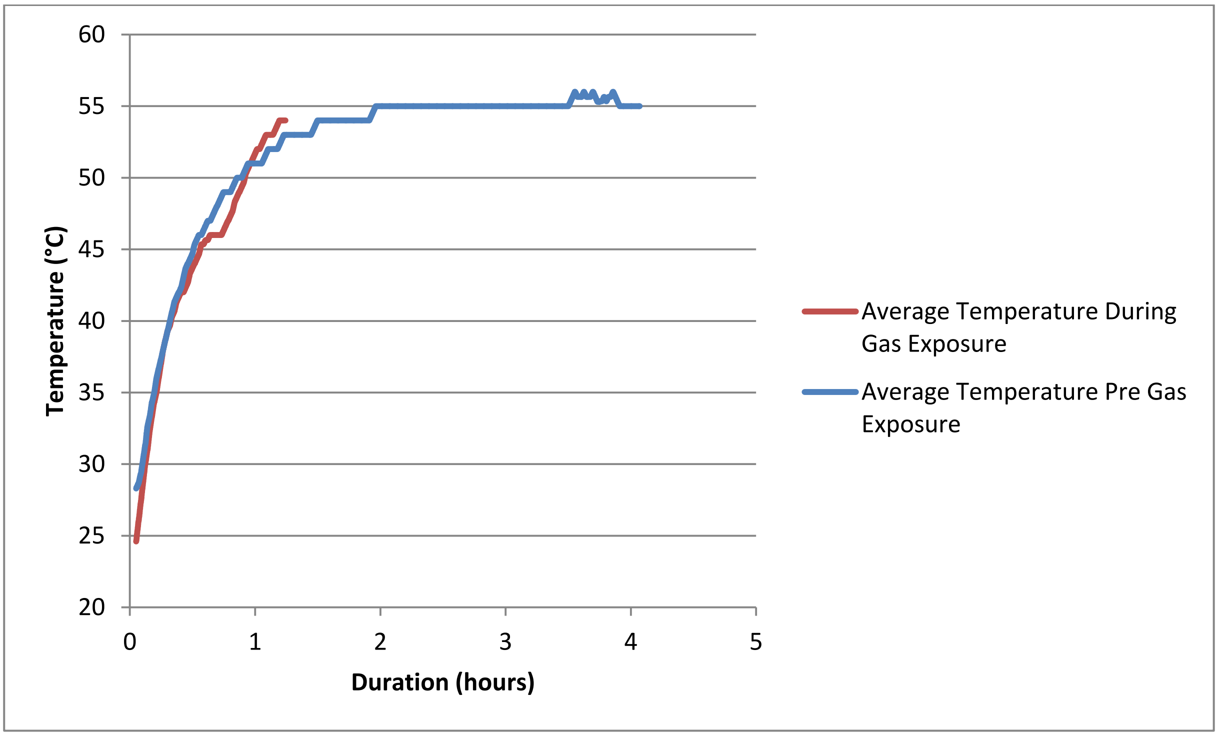


Figure F.18: Internal temperature of laptop 2 prior to and during gas vulnerability testing.

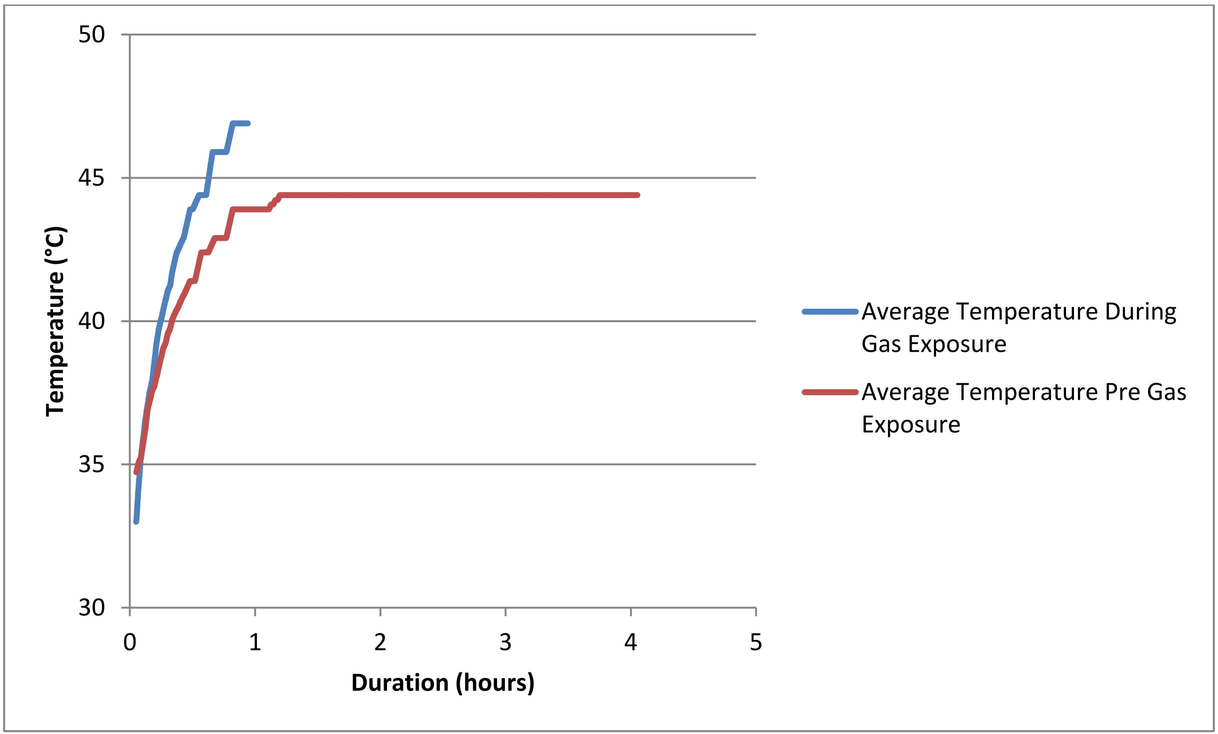


Figure F.19: Internal temperature of laptop 4 prior to and during gas vulnerability testing.